SAND2010-7436C

Introduction to NuMAD

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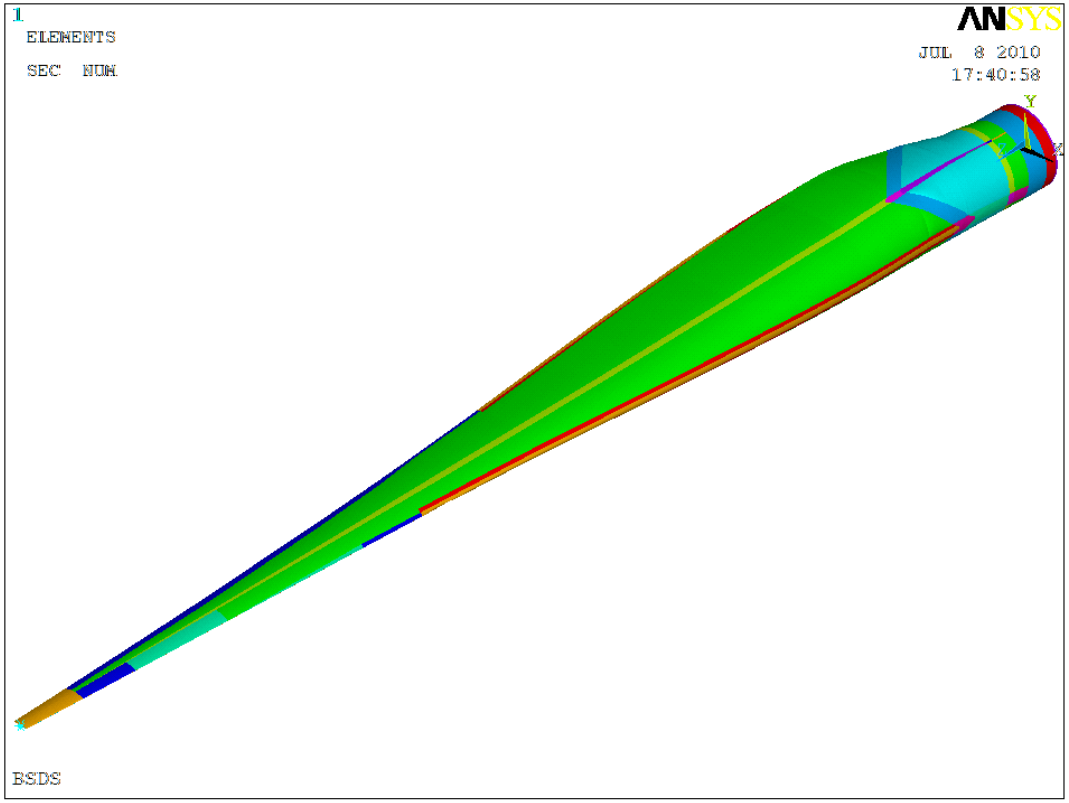
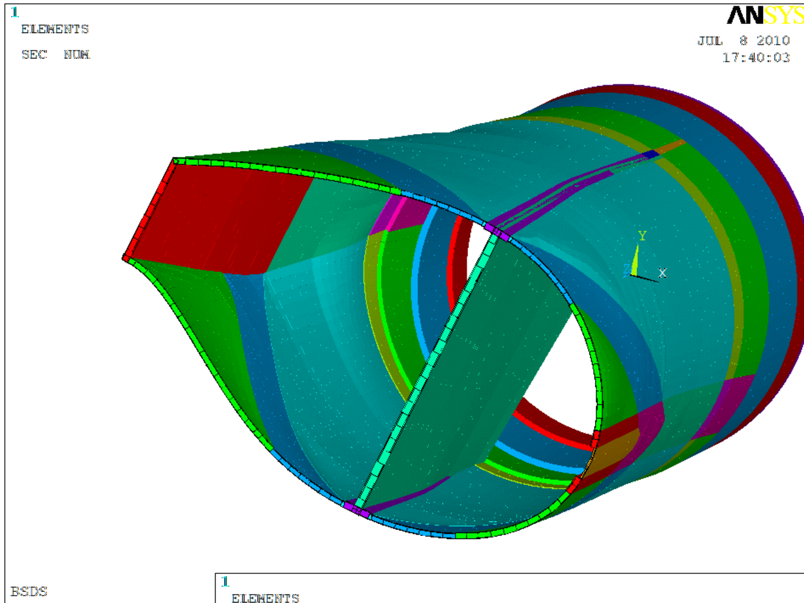
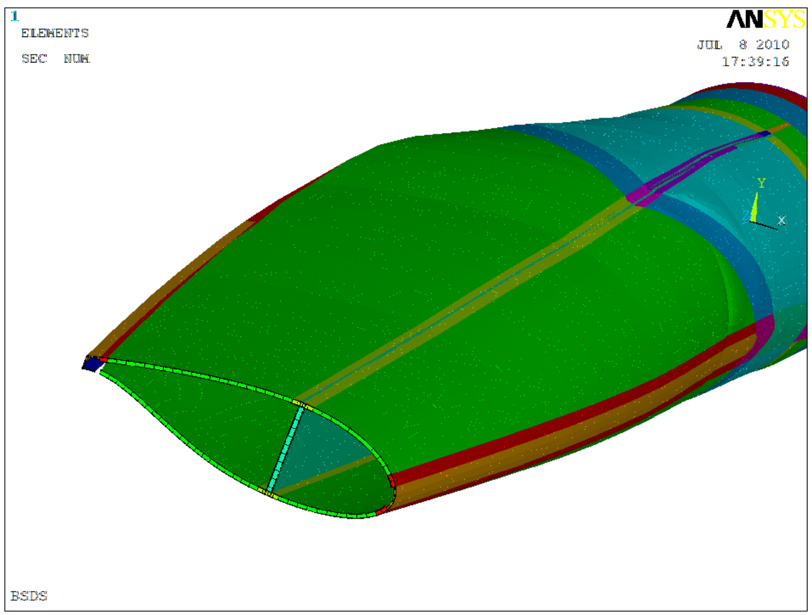
Blade example

- An example to get enthusiasm primed
- Open BSDS in NuMAD and ANSYS

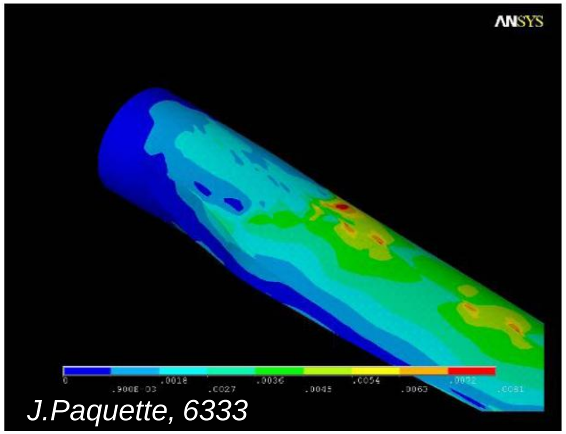


Analyses



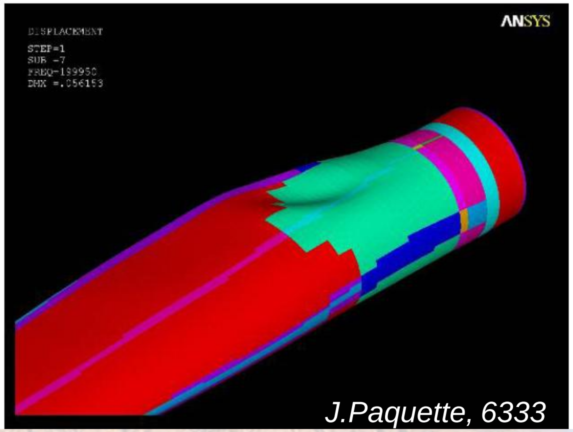


Stress & Strain



J.Paquette, 6333

Panel Buckling



J.Paquette, 6333

Introduction

- **My interests/goals**
  - To exposure students to all features in NuMAD
  - Demonstration of the entire model creation process on a simple wind turbine blade on your own computer
  - Immediate feedback on NuMAD usage
    - Evaluation forms to gather and save student feedback
- **Student interests/goals?**

NuMAD Tutorial Agenda

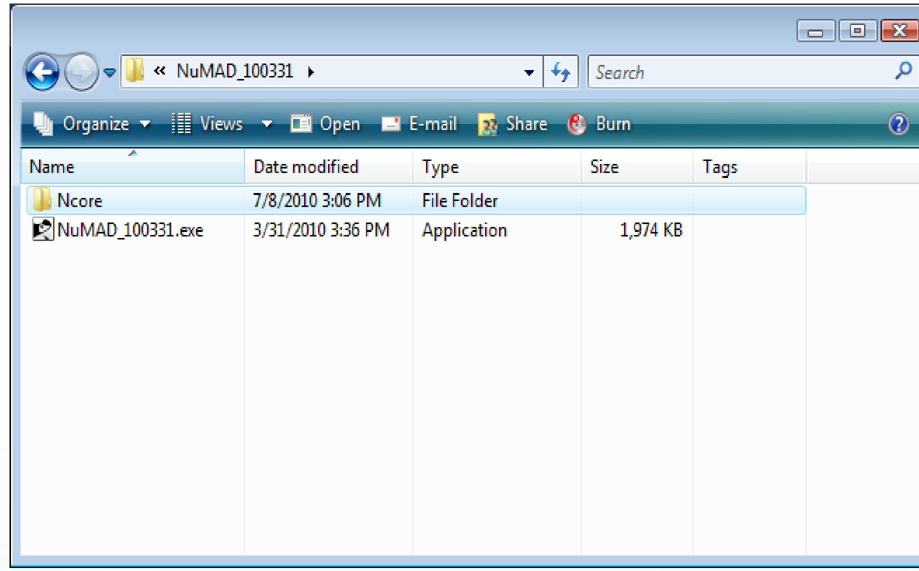
- **Day 1, 1 to 4pm, Thursday**
  - Files and directory structure
  - Blade geometry setup
  - Materials setup
  - Materials assignment
- **Day 2, 8am to lunch, Friday**
  - FE model creation
  - Analyses examples
  - Improvement on the blade design

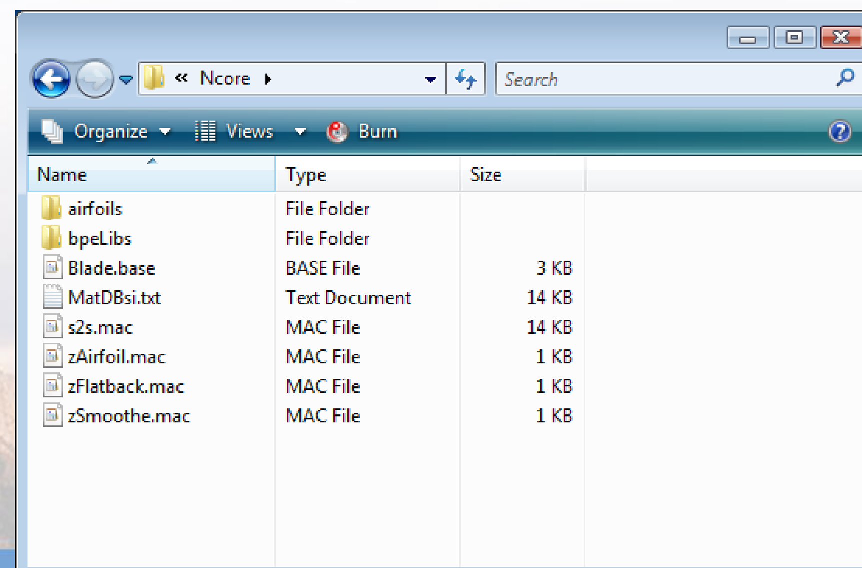
Session 1

- **Files and directory structure**
- **Goals:**
  - Install NuMAD
  - Tour the file structure
  - Work with airfoil data file
  - Show airfoil splining

Files and directory structure

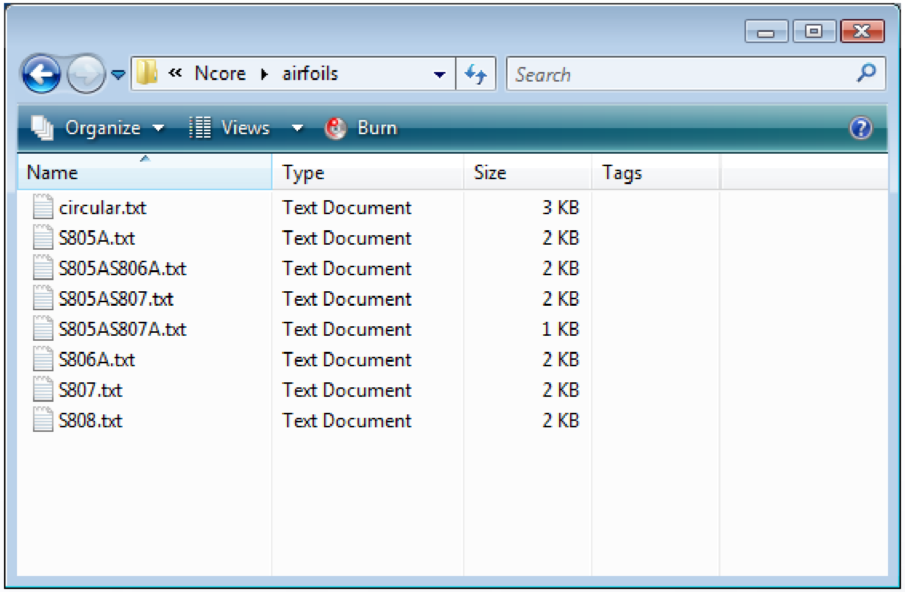
- **Distributed NuMAD Package**
  - NuMAD_100331.zip
  - Save it and duplicate it for each Turbine Blade Model
    - Ncore
      - **Ncore\Airfoils – Master airfoil files**
      - **Ncore\bpeLibs – Several necessary required to execute BPE with NuMAD**
      - **Miscellaneous important files**
    - Project Files
    - Settings.txt
    - Explain local vs. master files

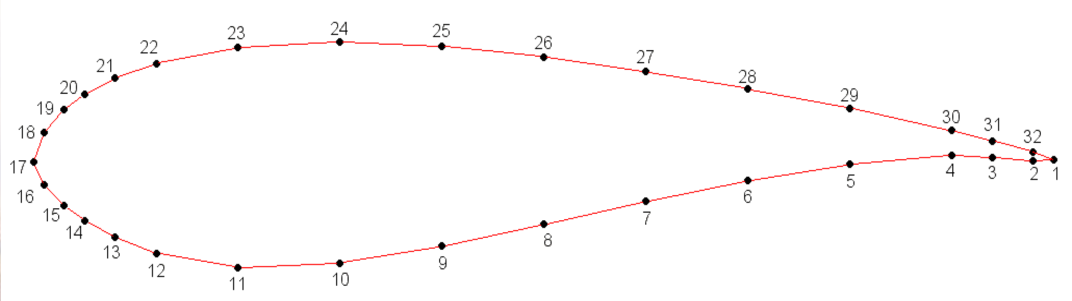




Airfoils

- **Coordinates**
  - Normalized coordinates
  - First coordinate at the TE (1,0)
  - Define the shape in a clockwise direction; i.e. TE, HP surface, LE, LP surface
  - Final coordinate pair does NOT duplicate the first coordinate pair
  - Number of pairs is not critical and does not have to be consistent between airfoils
- **Airfoils are loaded when NuMAD is launched**
- **Reminder: Local vs. Master airfoils**





Hands-On Exercise

- Create a pentagon airfoil
- LE and TE are on corners of the pentagon
- “Install” the airfoil file in NuMAD
- Load airfoil into NuMAD and view

- Possible coordinates:

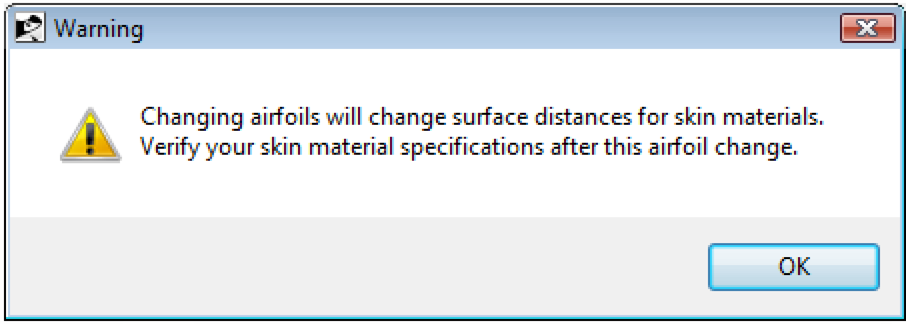
x	y
1	0
0.3	-0.1
0	0
0.2	0.2
0.45	0.2

Exercise Details 1

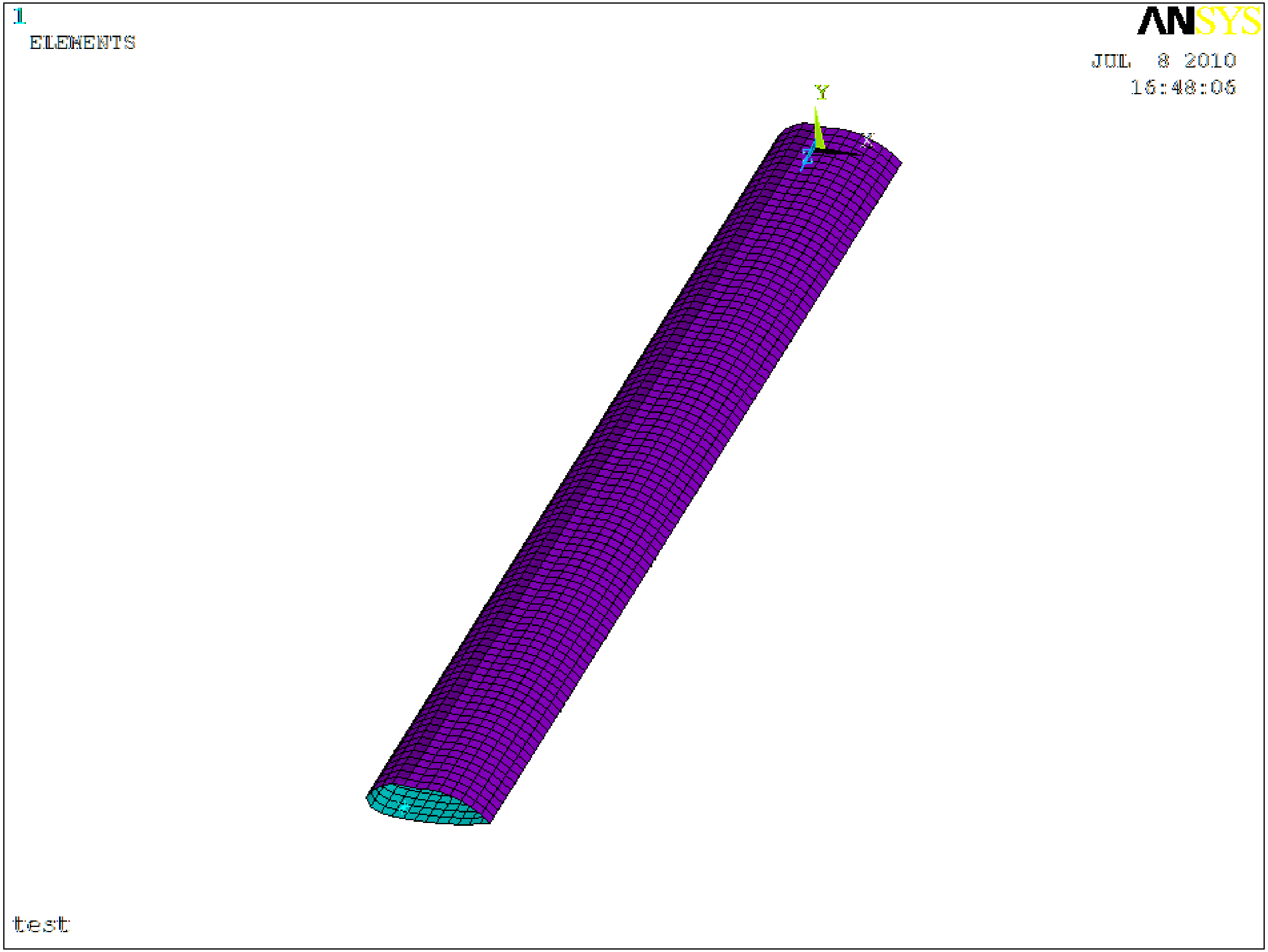
- **Airfoil File**
  - Begin by copy/pasting an existing airfoil file
  - Remember where to start the coordinate pairs, i.e. TE at (1,0)
  - Don’t duplicate the final point at the TE
- **Use the file in NuMAD**
  - Make sure file is in Ncore\airfoils
  - Start NuMAD (make ANSYS choice)
  - Create new project
  - Select a composite material for use in model, i.e. Steel
  - “Define Blade” using the GUI

Exercise Details 2

- Select and change the root airfoil (cylinder) to your airfoil (pentagon)
  - Choose OK when warning dialog appears …as seen at right>>
  - Be aware of the trailing edge type that you have defined
- Select and change the tip airfoil
- “Finish”; Done
- Optional; in ANSYS
  - Set boundary conditions, elements, and output (shell7 and db)
  - Set mesh size: Element size = 0.1m
  - Generate Model
  - View in ANSYS

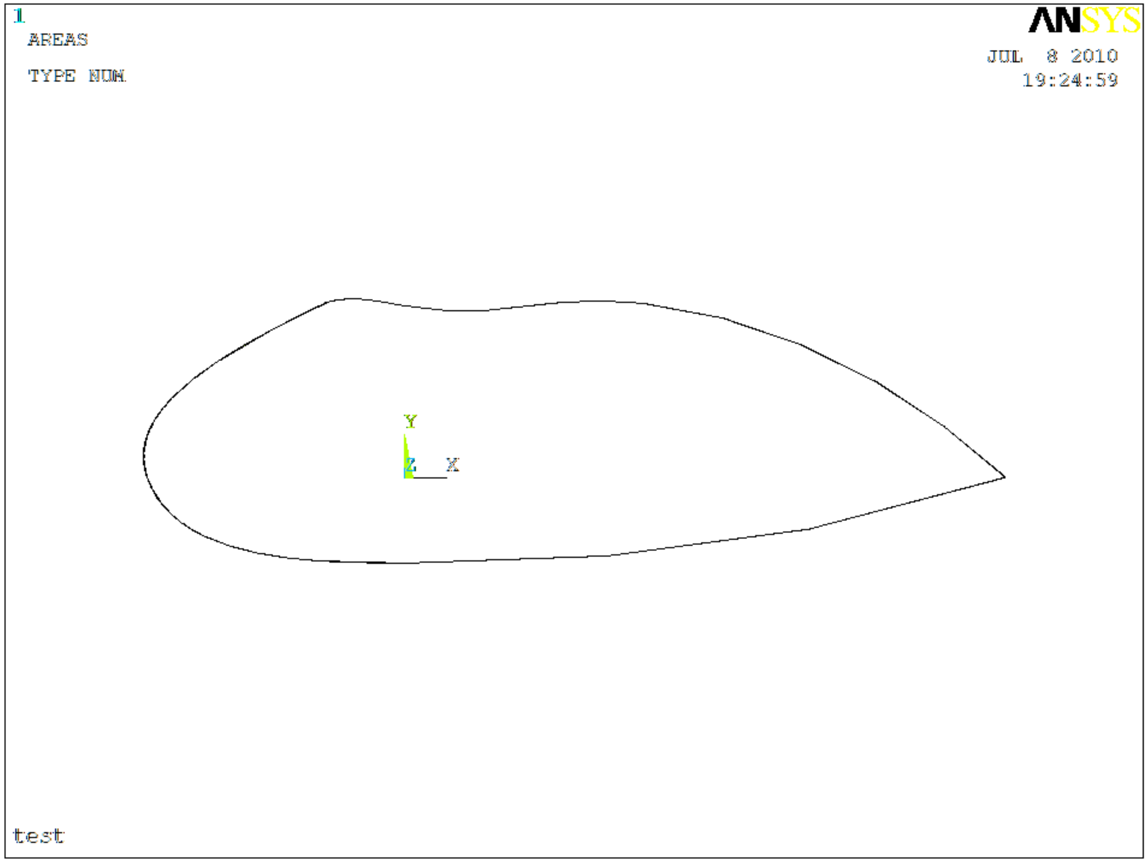


ANSYS Model



ANSYS Model

- TE Type: Sharp
- Talk about spline macros
  - zAirfoil.mac
  - zFlatback.mac
  - zSmoothe.mac



Session 2

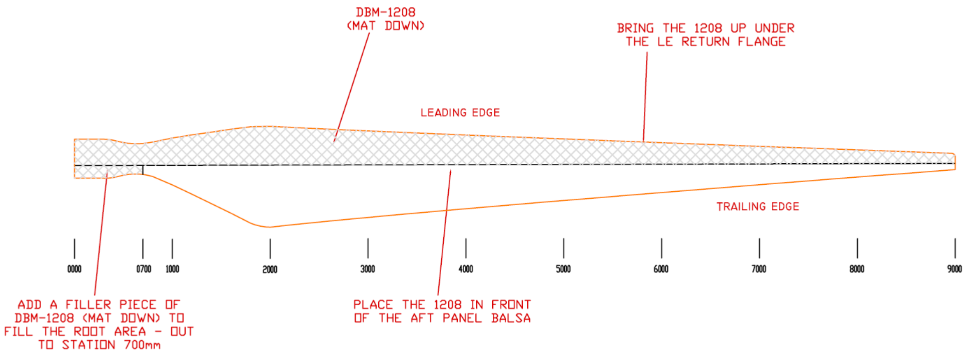
- **Blade Geometry**
- **Goals:**
  - Begin to set up a new wind turbine blade model

NuMAD model ingredients

- **Blade geometry**
  - Airfoil coordinates and span locations
  - Chord distribution
  - X-offset distribution
  - Airfoil twist distribution
- **Materials**
  - Materials
  - Effective material properties:
    - Isotropic
    - Orthtropic
    - Ex, Ey, Ez, Gxy, Gyz, Gxz, PRxy, PRyz, PRxz, density
  - Layup or “Stack” consisting of multiple layers of composites and materials

NuMAD model ingredients (2)

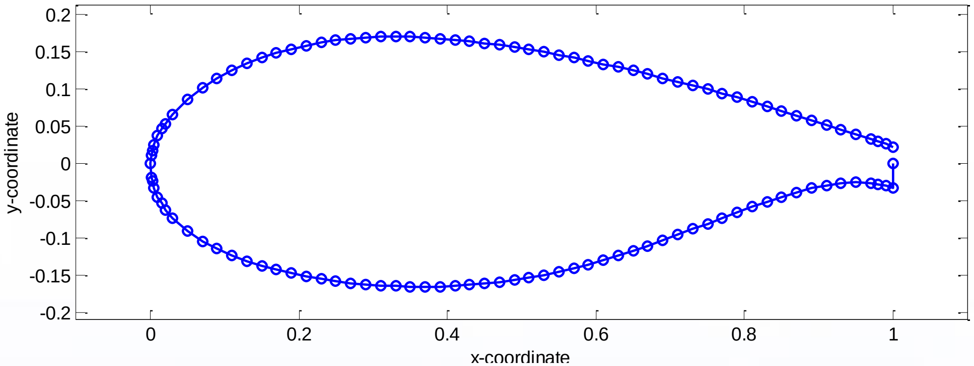
- **Stack placement; i.e. blade skin layup design**
- **An example of a single layer:**

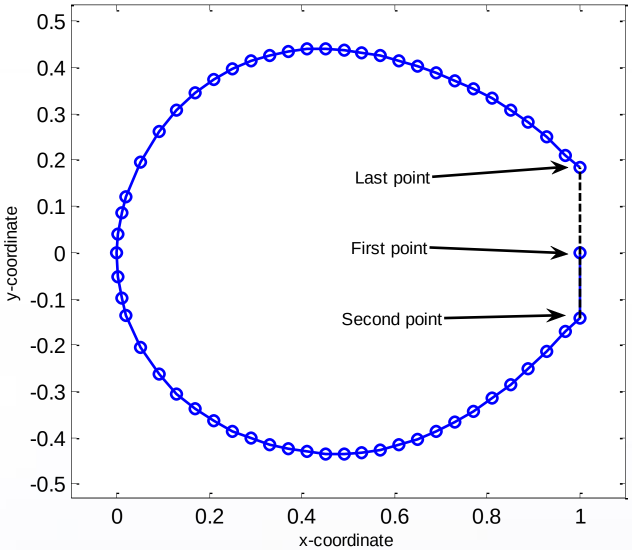


- **Areas of interest:**
  - Root, LE panels (with and without core), spar caps, shear webs, TE panels (with and without core)
  - Decisions have to be made regarding how to represent individual ply drops along span, especially in root

Airfoil TE Types

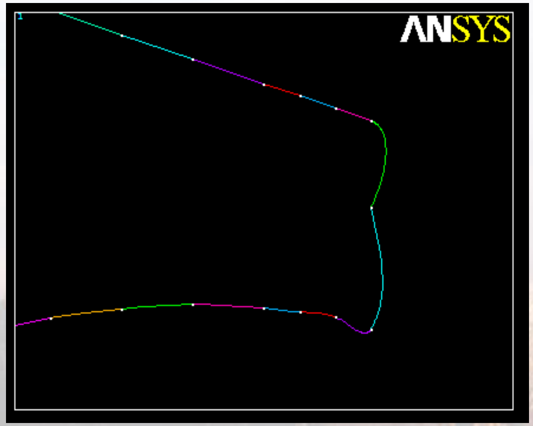
- **Circular, sharp, flat**



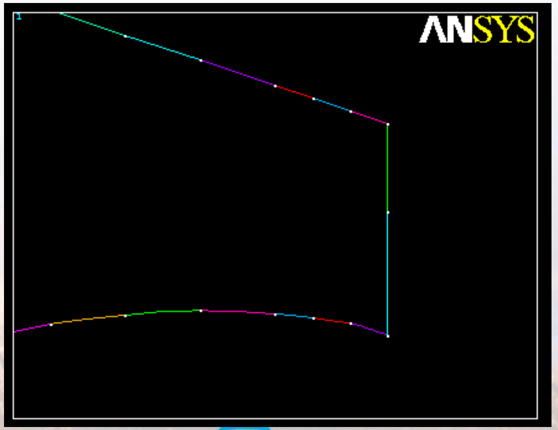


Smooth (circular)

Sharp



Flat



Hands-On Exercise

- **Beginning a blade:**
- **WindPact 1.5MW blade**
  - See references in "A 1.5 MW NuMAD Blade Model" provided as hard copy

- **Begin with basic blade geometry in this exercise**

Creating Blade Geometry

- **Copy airfoil files S818, S825, S826 into the master airfoils directory**
  - Airfoils: Ex2_BladeGeometry\WP_Airfoils
  - Master: Ex2_BladeGeometry\NuMAD\Ncore\airfoils
- **Start NuMAD**
- **In NuMAD: File -> New Model**
- **Type name for new project, WP_Blade**
- **Set units**
- **Select a material for use, Steel (from the Composite List, not the raw material, this way there is a material thickness associated with it)**
  - Right-click “Steel”
  - See it appear in the “selected composite materials” dialog box
  - Press “OK” in the “currently defined materials” dialog
- **Blade-> Define ->GUI**

Entering Blade Geometry

- **For each station, get information from WP_NuMAD Report, Table 7 "Blade information at each station"**
  - Airfoil
  - TE type
  - Twist (deg)
  - Chord (m)
  - X-offset (-)
  - Aerodynamic center (leave default of 0.25)
  - Distance from root (m)
- **With all stations complete, you have your basic blade geometry**

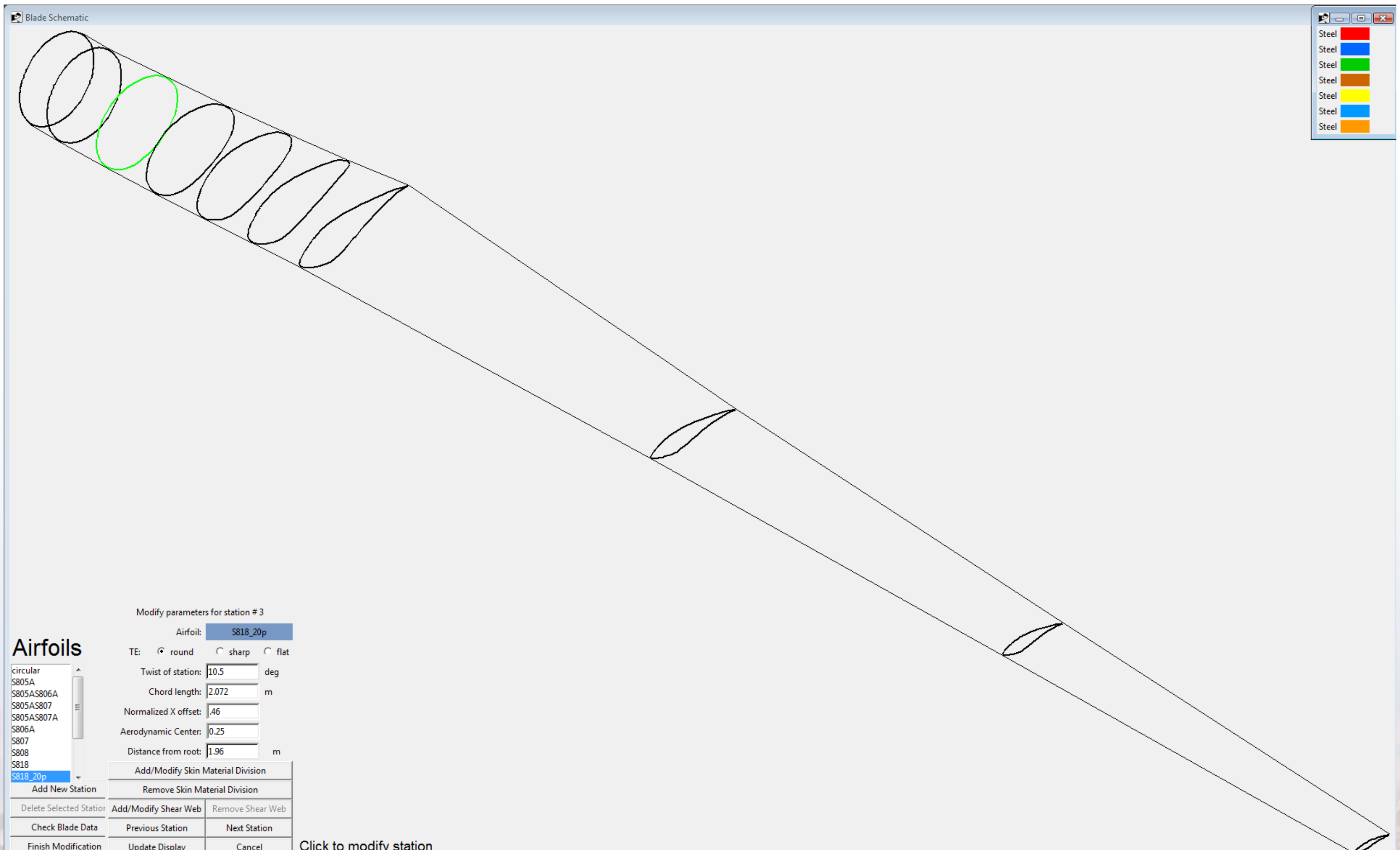
Addition of root stations

- Additional root stations will help in defining the root region later on.
- These stations are not called out in the WindPact reports
- The airfoil shapes here are simple linear interpolations of a circle and the S818 airfoil.
- The shapes provided here do not claim to be the best for optimal design.

Station #	Airfoil	Span (m), Distance from root	Twist (deg)	Chord (m)	X-offset (-)
2	Circ.	0.7	10.5	1.89	.5
3	S818_20p	1.96	10.5	2.072	.46
4	S818_40p	3.22	10.5	2.254	.42
5	S818_60p	4.48	10.5	2.436	.38
6	S818_80p	5.74	10.5	2.618	.34

Final Product

- See 'Ex2_BladeGeometry\FinishedFiles' for finished files

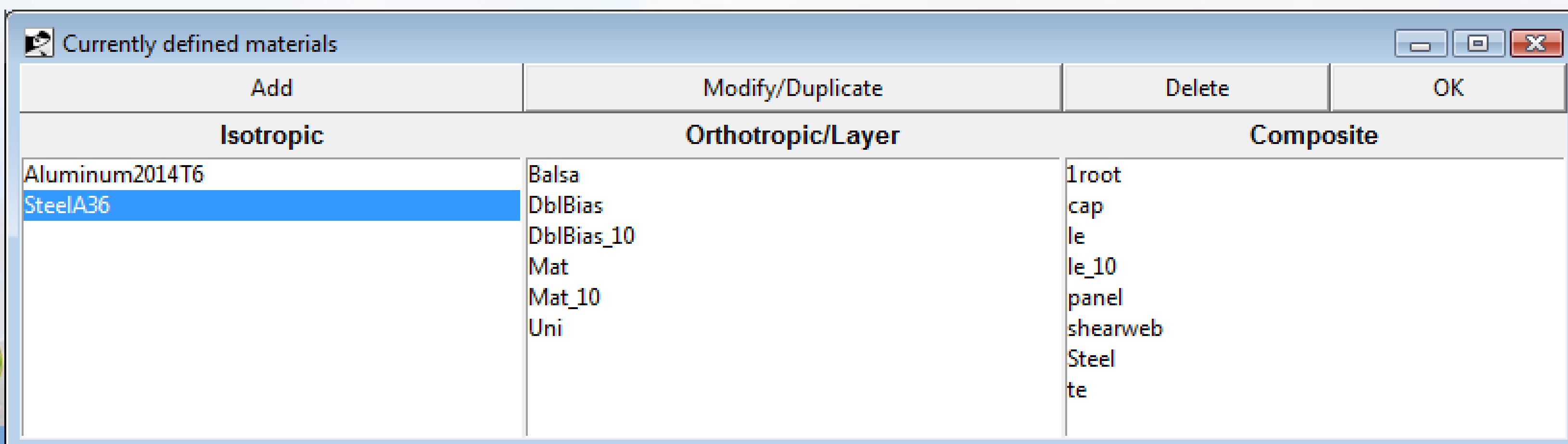


Session 3

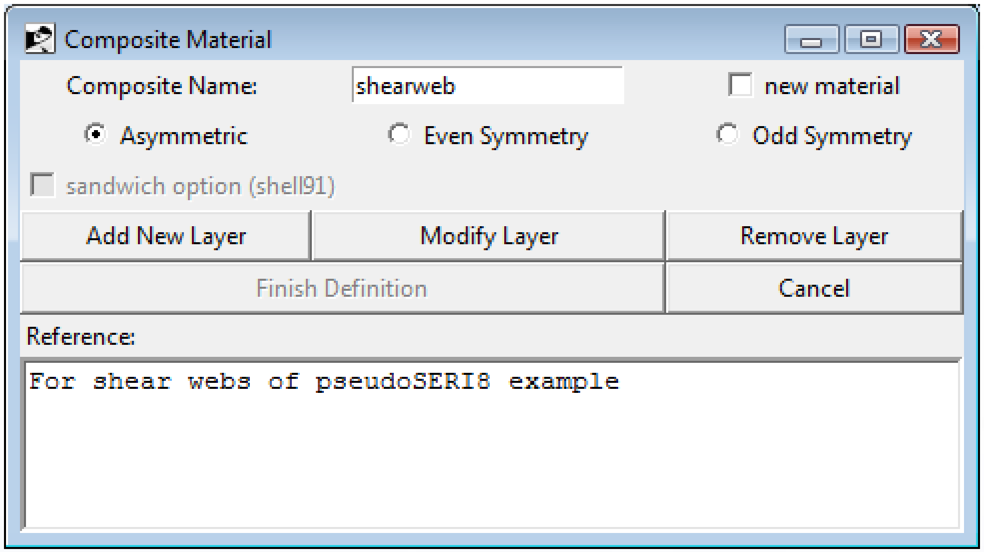
- **Material Property Management**
- **Goals:**
  - Understand the different types of entries in the materials database
  - Enter materials and stacks that are necessary for the blade model

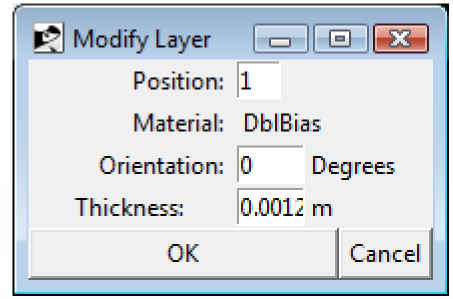
Materials Management

- **Terminology**
  - Materials
    - “Isotropic”
    - “Orthotropic”
    - Both can serve as layers
  - “Composite” Stack
    - One or more layers of Materials
    - Includes thickness and fiber orientation

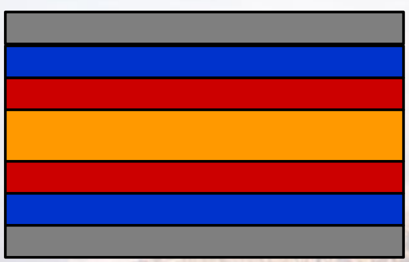


Defining Composite Stacks

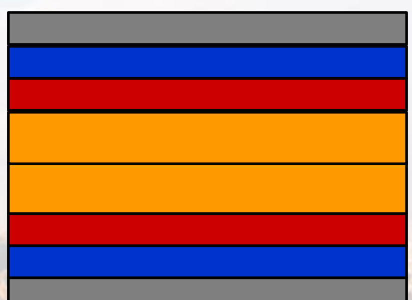




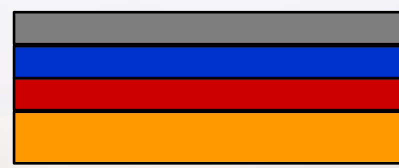
Odd symmetry



Even symmetry

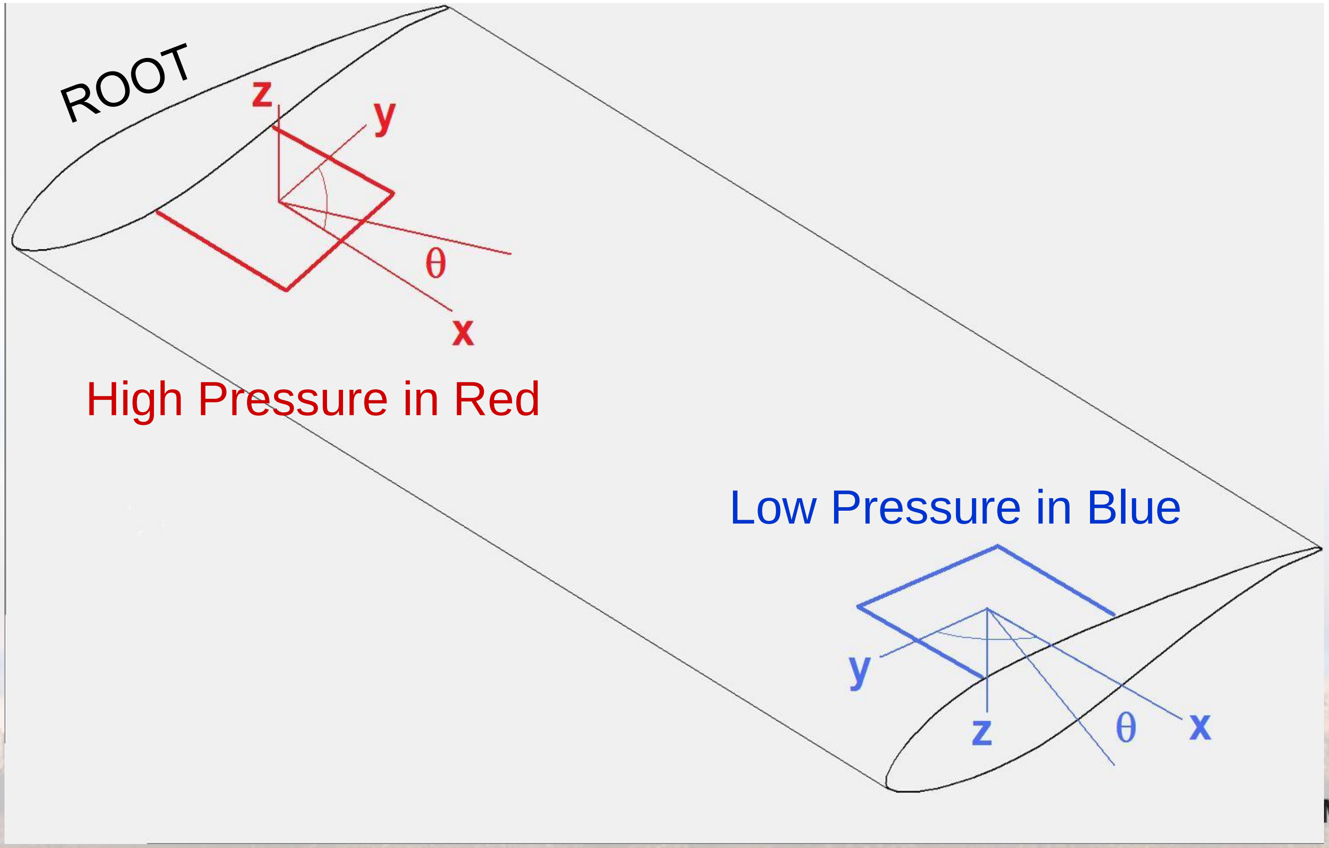


Asymmetric



Defining Composite Stacks

- **Layer Orientation**
  - Orientation is different on HP and LP surface
  - Local material coordinate systems (x y z) shown below



Exercise

- **Add materials to the WP_Blade materials database**

Material Properties

- **Start NuMAD**
  - Ex3_Materials\NuMAD
- **Open blade model**
  - Ex3_Materials\NuMAD\WP_Blade
- **Go to the Materials Menu and add the following materials for use in the WP Model. Properties are found in "WP_NuMAD_Report" Table 3:**
  - Gel_Coat
  - Balsa
  - Random_Mat
  - A260CDB340_Spar_Mix
  - CDB340Epoxy

Composite Stacks

- Using the materials just added, create composite stacks for use in the WP Blade
- Stacks vary with placement in cross section. Suggest using the following base naming convention
- See next slide….

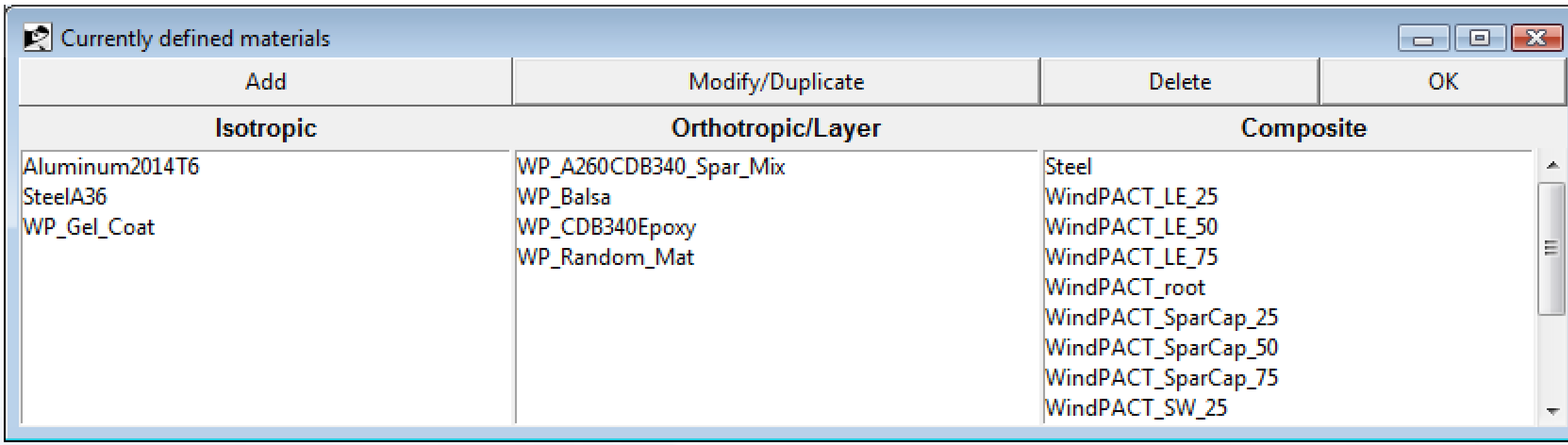
Region	Base name
LE panel	WindPact_LE_
Spar cap	WindPact_SparCap_
TE panel	WindPact_TE_
Root	WindPact_root
Shear web	WindPact_SW_

Composite Stacks

- **Stack thicknesses vary with blade span, so create a different stack for each span location**
- **To the base names, append a suffix that indicates span location; i.e. 25, 50, 75**
- **End up with the following 12 composite stack definitions:**
  - Leading Edge: WindPact_LE_25, WindPact_LE_50, WindPact_LE_75
  - Spar Cap: WindPact_SparCap_25, WindPact_SparCap_50, WindPact_SparCap_75
  - Trailing Edge: WindPact_TE_25, WindPact_TE_50, WindPact_TE_75
  - Root: WindPact_root
  - Shear Web: WindPact_SW_25, WindPact_SW_50
- **Layer details for each stack are found in the "WP_NuMAD Report" Table 4, 5 & 6**
  - Tables 4 and 5 set thicknesses to be functions of blade geometry. Find an example of calculated thicknesses in "WP_NuMAD Report" Table 8.
- **!!! Use the "Modify/Duplicate" button excessively to make this as efficient as possible**

Finished Product

- See 'Ex3_Materials\FinishedFiles' for final product

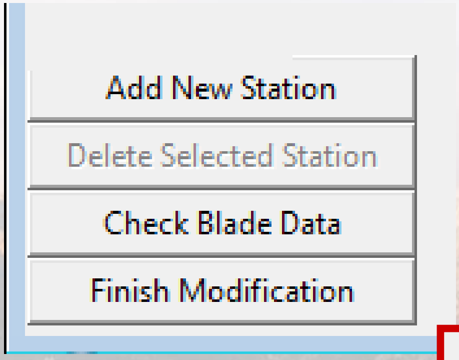


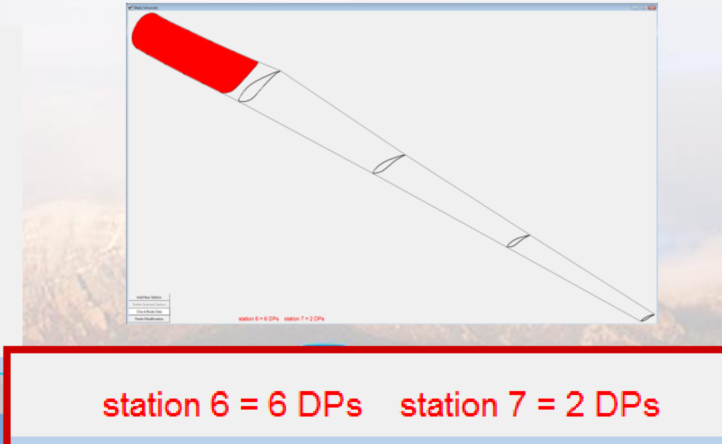
Session 4

- **Materials Placement**
- **Goals:**
  - Introduce material delineation points
  - Demonstrate how to enter and manage delineation points
  - Demonstrate how to assign material stacks to the blade geometry
  - Add shear webs and assign shear web materials

Delineation Points

- **Delineation points are used to divide the blade into areas**
- **The areas represent different materials which comprise the surface of the blade**
- **Each station must have a minimum of two delineation points**
  - Two points are added by default when stations are created
- **The number of delineation points from station to station must be consistent**
  - Consistency is check with the "check blade data" button both for the
    - Station level or
    - Overall blade level:

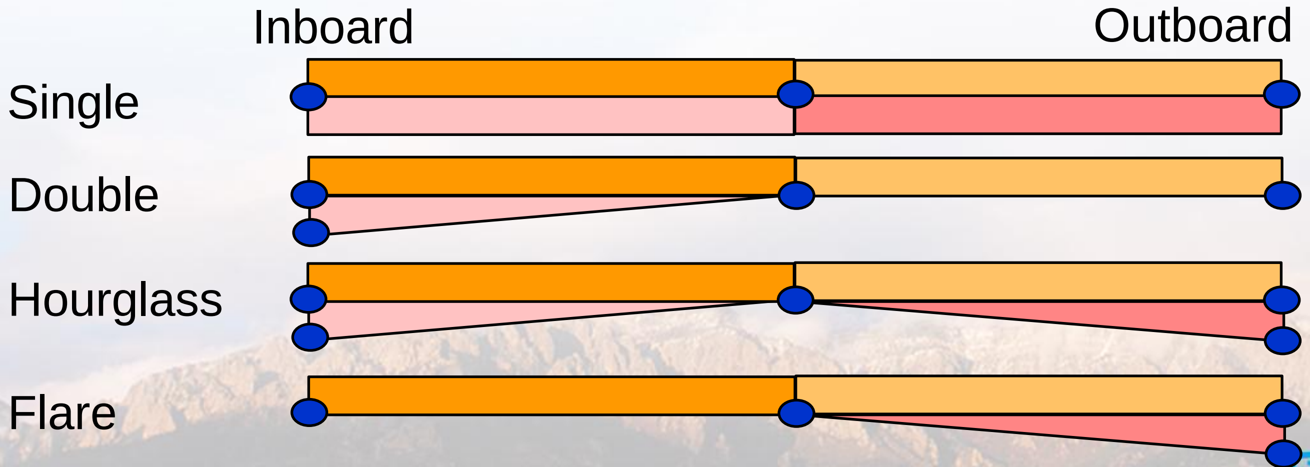




More Delineation Points

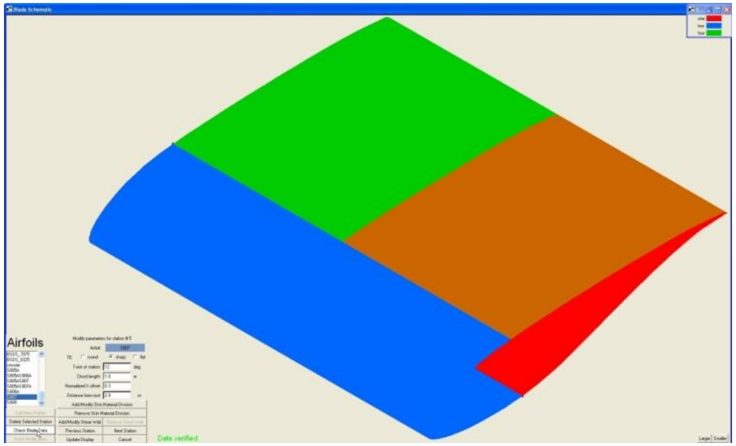
- **The number of delineation points can change from station to station when using triangular areas**

Type of Triangular Delineation Point	Maps from (number of points on station inboard)	Maps to (number of points on station outboard)
Single	1	1
Double	2	1
Hourglass	2	2
Flare	1	2

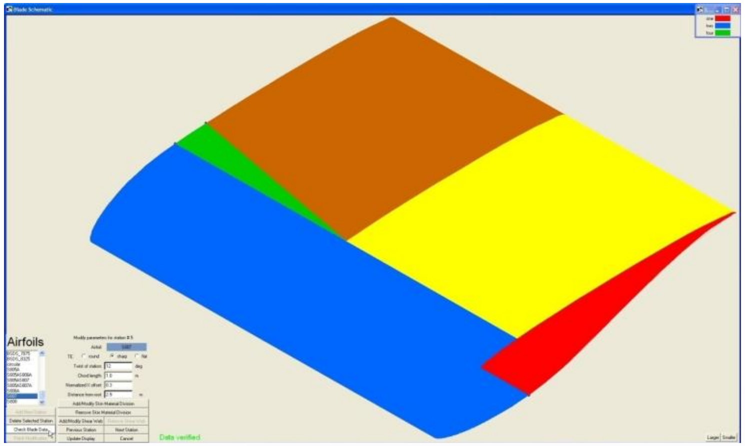


More Delineation Points

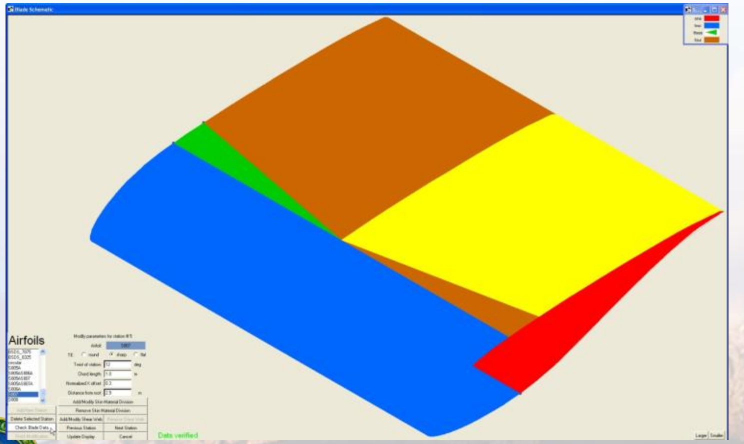
SINGLE



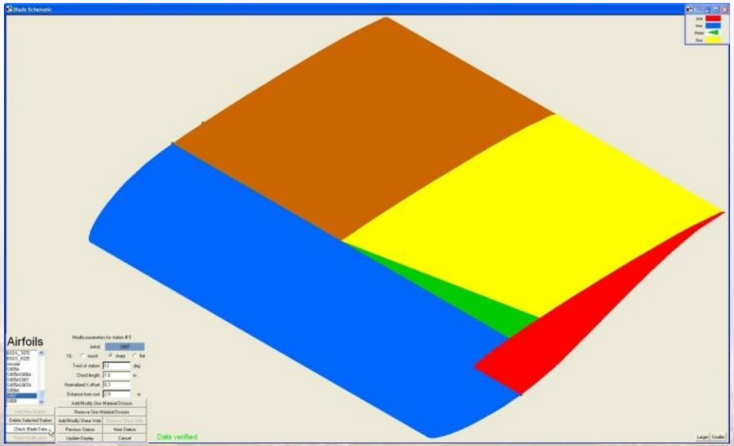
DOUBLE



HOURGLASS

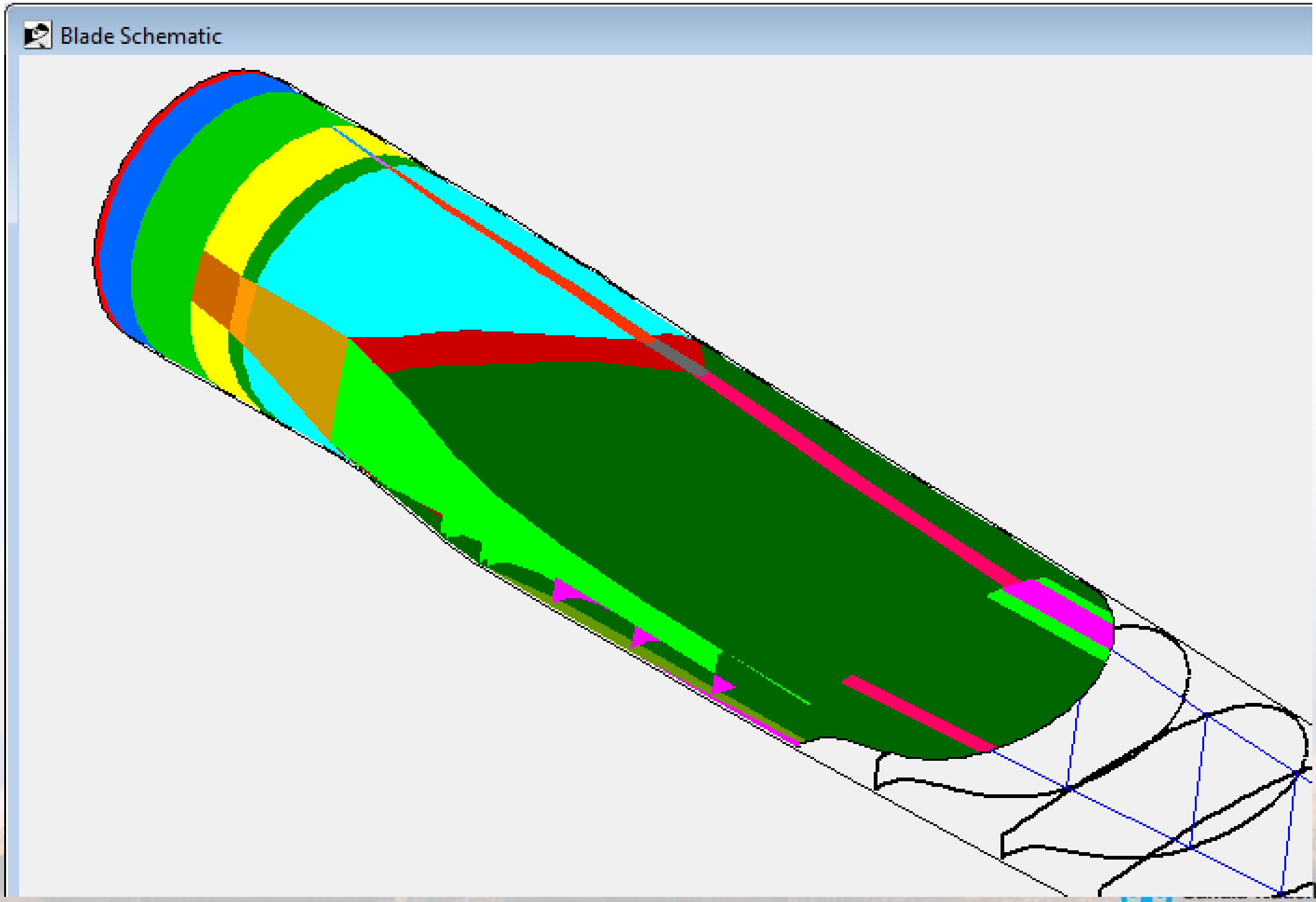


FLARE



Blade with defined areas

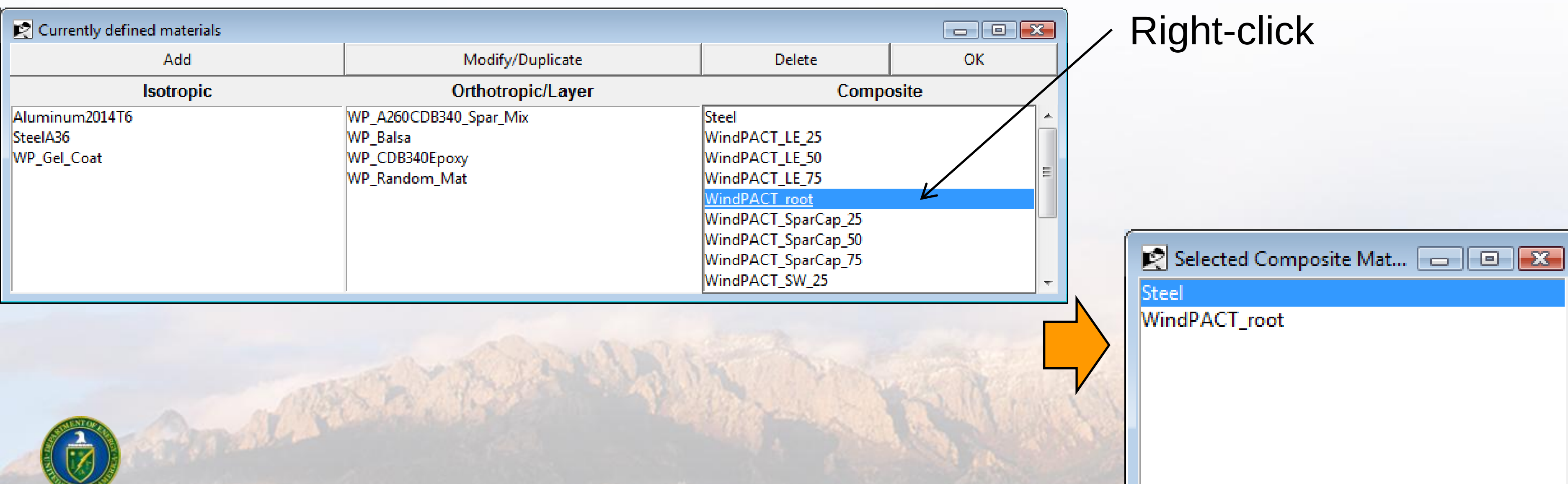
- **A complicated example:**



Exercise

- Assign composite stacks to the example blade

- **Begin with model in Ex4_MaterialAssignment\NuMAD**
- **Add composite stacks to the "Selected Composite Materials" list**
  - In the menu "Materials->Composite" right click on names to add them to the "Selected Composite Materials" list, which is another dialog box that will appear



Assign materials

- **Add all the following composite materials to the “Selected” list:**
  - WindPact_LE_25, WindPact_LE_50, WindPact_LE_75
  - WindPact_SparCap_25, WindPact_SparCap_50, WindPact_SparCap_75
  - WindPact_TE_25, WindPact_TE_50, WindPact_TE_75
  - WindPact_root
  - WindPact_SW_25, WindPact_SW_50
- **Click on “Blade->Display/Modify”**
- **Choose a station by clicking on the graphic for the station**

Assign materials to root

- **Assign a material to a segment with the following steps:**
  - Left-click on segment to highlight
  - Left-click material name in dialog box (WindPact_Root)
  - Left-click on segment to un-highlight and set material
  - !! It is tempting to assign multiple segments at once; Failure to follow these three steps for EACH segment of material will result in incorrect assignments.
- **Note that some materials have already been defined in stations 3 thru 5 (WindPact_Root)**
- **Note that material delineation points have been already defined for the root sections: 2%, 15% and 50% chord on both the LP and the HP surfaces**

Assign materials beyond max chord

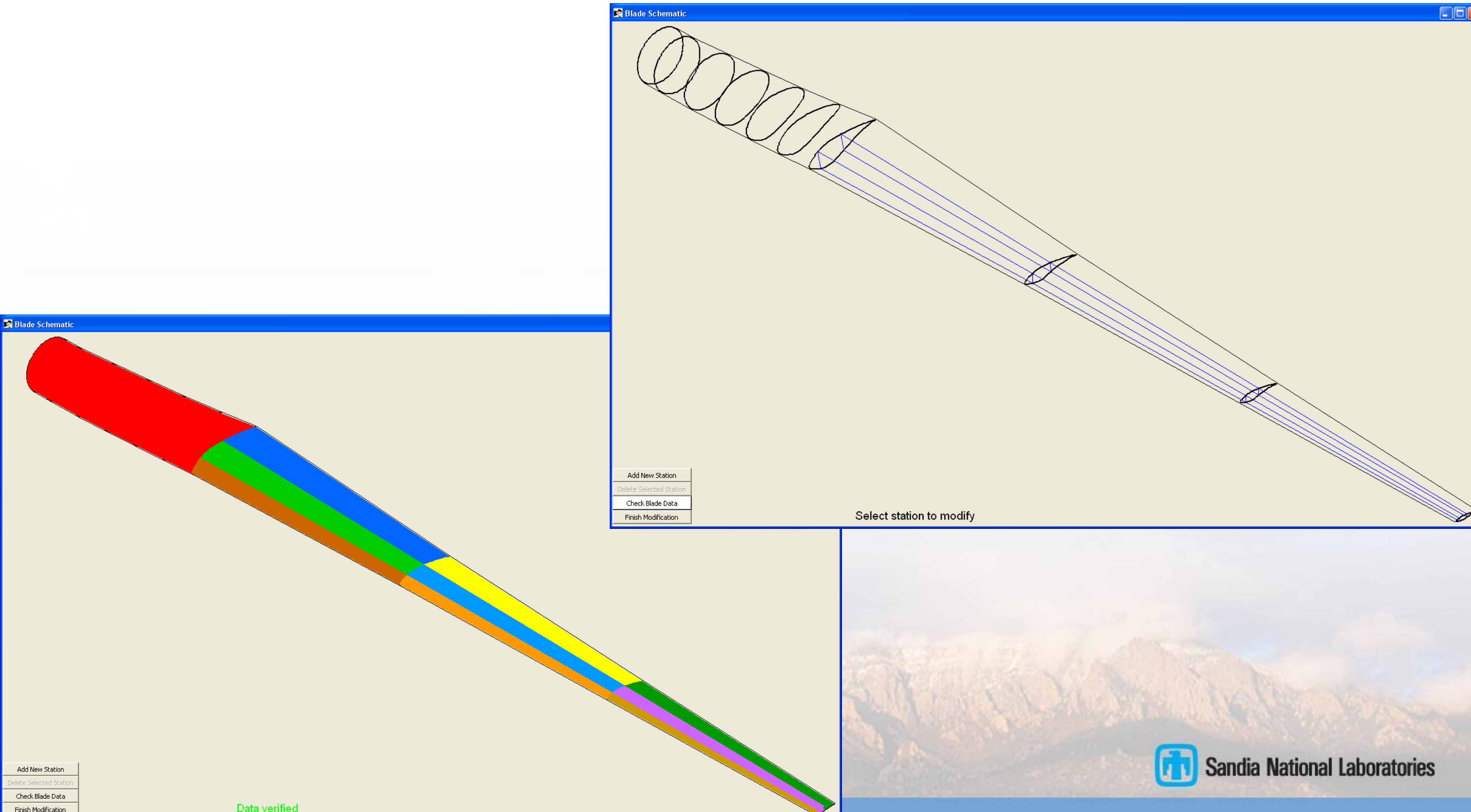
- **Max chord begins at NuMAD Station #7**
- **Following are guidelines for assignment of materials outboard of this point (inclusive)**
  - Add material delineation points on both HP and LP surface of type “Single” at 2% chord (optional), 15% chord, and 50% chord
  - Assign materials as follows:
    - In front of 15% chord: WindPact_LE_X
    - Between 15 and 50% chord: WindPact_SparCap_X
    - Aft of 50% chord: WindPact_TE_X
    - X = the span location (i.e. 25% span, 50% span and 75% span)
      - **Remember that some material thicknesses are a function of chord, which is a function of span location.**

Shear web assignment

- **Shear webs are present in this model beginning at Station 7 (max chord) and ending at the blade tip**
- **There are two shear webs: one at 15% chord and one at 50% chord; they comprise what's called a "box spar"**
- **See Figure 2 in the WP_NuMAD_Report for illustration of shear webs**
- **The process:**
  - Select a station where a shear web is to begin (e.g. Station 7)
  - Click the button for "Add/Modify Shear Web"
  - Set "DP" numbers to put shear web where it belongs
  - Left-click on a material for the shear web
  - Click the "Add Shear Web" button
  - Repeat, to add second shear web

Finished product

- See ‘Ex4_MaterialAssignment\end’ for finished NuMAD model



Session 5

- **Finite element (FE) model creation**
- **Goals:**
  - Demonstrate NuMAD output into ANSYS capabilities
  - Show high level steps used to create the ANSYS FE model

Turbine blade FE basics

- **Discussion of ‘shell7.src’ commands**
- **Elements discussion – Old shell formulations**
- **Elements discussion – New shell formulation**
- Summary: Shell element choices (91 vs 99 vs 281)
- Boundary conditions
- Mesh – AESIZE vs Smart Size
- Mesh – mesh density recommendations

Generation of ‘shell7.src ‘

- **A “Check Blade Data” is performed automatically prior to shell7 generation to ensure consistency of material delineation points**
- **The shell7 file is generated by NuMAD regardless of ANSYS installation status**
- **ANSYS APDL commands in the shell7 file are used to generate the entire FE model in ANSYS, either**
  - In ANSYS batch mode, following the shell7.src file generation
  - From ANSYS Mechanical APDL via the /INPUT command
- **The shell7 file is saved in the NuMAD project directory**

Explanation *of 'shell7.src' commands (1)*

- **Set number of errors**
- **Set filename**
- **/PREP7**
  - Define element types
    - SHELL99
    - SHELL91
    - Mass
    - SHELL281

Elements discussion - Offset thickness nodes

- **Offset-thickness nodes are most desirable for wind turbine blade FE models**
- **The outer blade surface is the surface that is specified**
- **Figures from *Laird, et.al. (2005)***

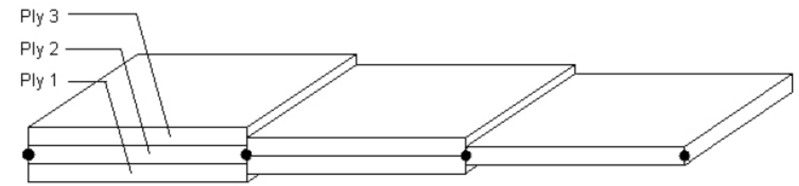


Figure 2. Schematic of physical representation of layered shell elements with nodes positioned at the mid-thickness.

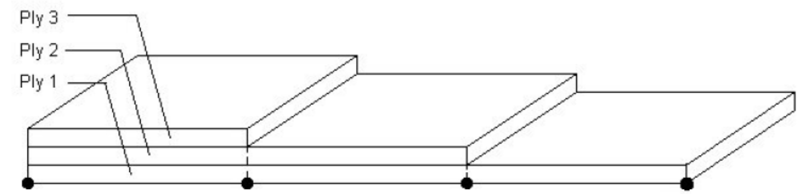
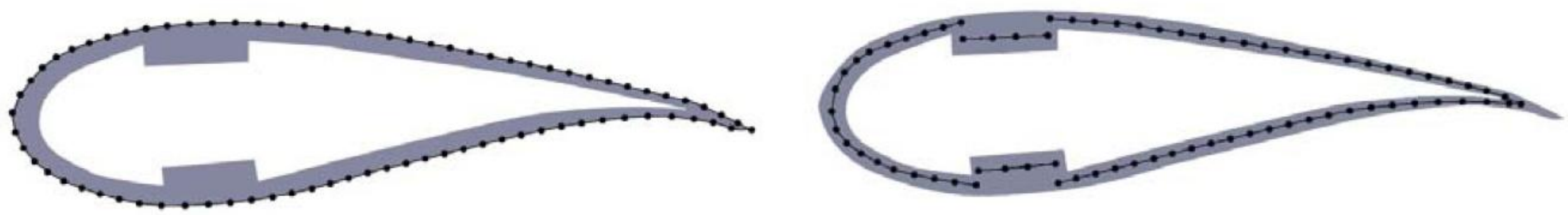


Figure 3. Schematic of physical representation of layered shell elements with nodes offset to the bottom surface.[1]

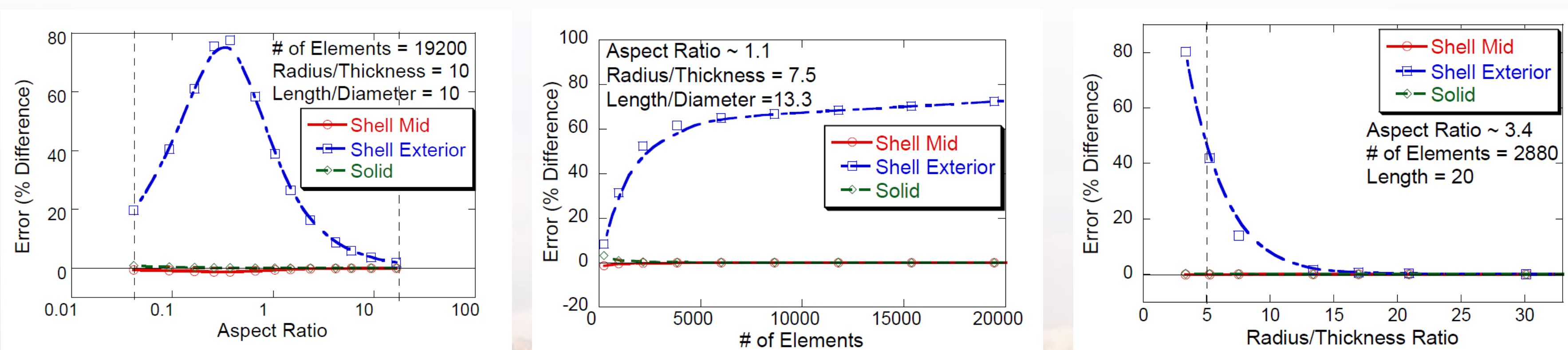


(a) (b)

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

Elements discussion – Old shell formulations

- **Laird, D. L.; Montoya, F. C. & Malcolm, D. "Finite Element Modeling of Wind Turbine Blades." *Wind Energy Symposium: 43rd AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2005-195,* 2005.**
  - Results indicate that the standard method of modeling full wind turbine blades with FEA, layered shell elements with offset nodes, is inaccurate with respect to torsional stiffness determination and shear stress due to torsional loading. This approach may also be problematic in bending for cases of very low radius/thickness ratio. Alternative element configurations exist to solve these problems and should be seriously considered for the designs of twist-bend coupled wind turbine blades.



Figures from *Laird, et.al. (2005)*

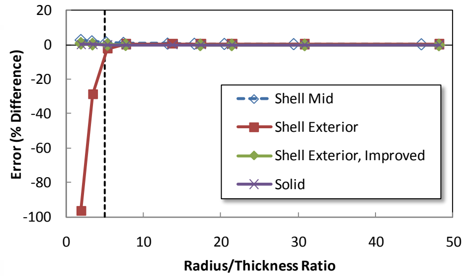
Elements discussion – New shell formulation

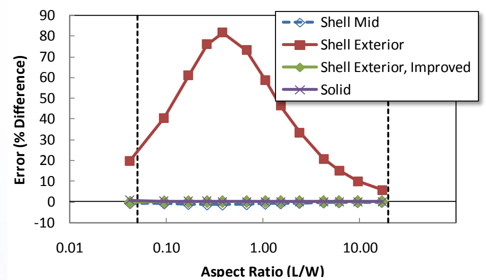
- **With release of ANSYS 12.0, there are changes to shell element offerings:**
  - **Layered shells SHELL91 and SHELL99 are "undocumented"**
  - **SHELL281, 8-node structural shell, is offered as a replacement**
- **SHELL281 features:**
  - **May be used for layered applications for modeling laminated composite shells or sandwich construction**
  - **Thickness Definition Using Real Constants**
  - **Layered Section Definition Using Section Commands**
  - Makes available an improved shell formulation that incorporates initial curvature effects more accurately:
    - both shell-membrane and thickness strains are accounted for in the calculation of effective shell curvature change
    - generally leads to better accuracy in curved shell structure simulations, especially when thickness strain is significant or the material anisotropy in the thickness direction cannot be ignored
    - computational cost associated with the improved formulation is slightly higher than that of the standard formulation
  - **See the ANSYS Help files for much more information**

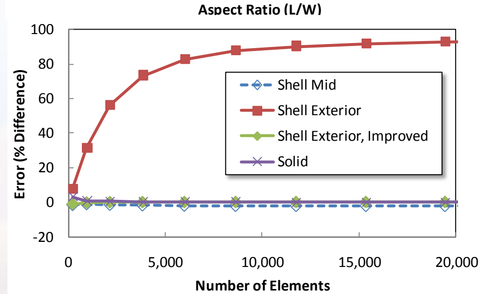
Elements discussion – New shell formulation

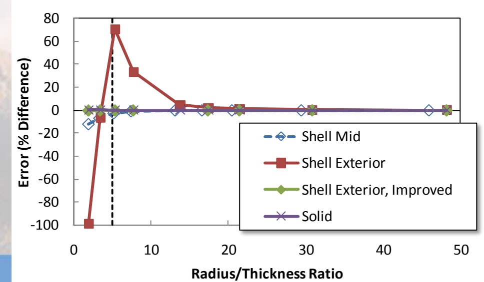
- **Redo the AIAA 2005 investigations using new formulation:**
- **Bending stress:**
  - Radius to thickness
- **Shear:**
  - Element aspect ratio
  - # elements
  - Radius to thickness

Results including old formulation (Shell Exterior)

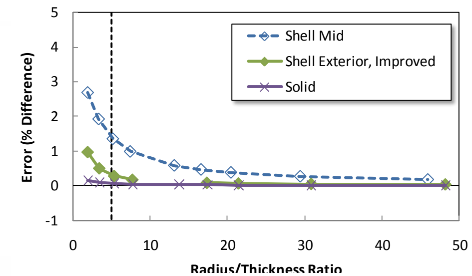


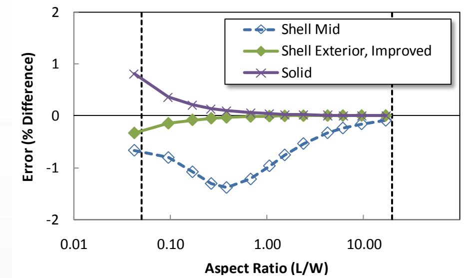


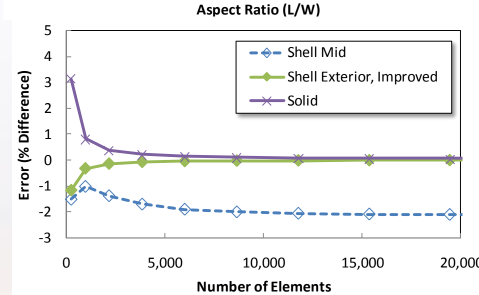


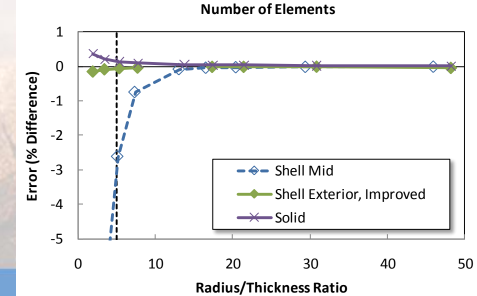


Results not including old formulation









Summary: ANSYS Shell element choices (91 vs. 99 vs. 281)

8-node shells:	SHELL91	SHELL99	SHELL281
Description	Nonlinear Layered Structural Shell	Linear Layered Structural Shell	Structural Shell
Functionality	Layered applications of a structural shell model or for modeling thick sandwich structures	SHELL99 may be used for layered applications of a structural shell model.	The SHELL281 element is suitable for analyzing thin to moderately-thick shell structures
ANSYS version	up to v11; undocumented in v12	Up to v11; undocumented in v12	v12 and higher
Includes nonlinearities	Yes	No	Yes
Sandwich option	Yes	No	Yes
Number of layers possible	100	250 (more possible)	Unlimited (?)
Element formulation time	--	Faster than SHELL91	Good
Materials/Layers defined via	Real constants	Real constants	Section data
Limitations t, total shell thickness R, radius of curvature	Require: $t < 2*R$ Recommend: $t < 0.2*R$	Require: $t < 2*R$ Recommend: $t < 0.2*R$	None, if KEYOPT(2)=1

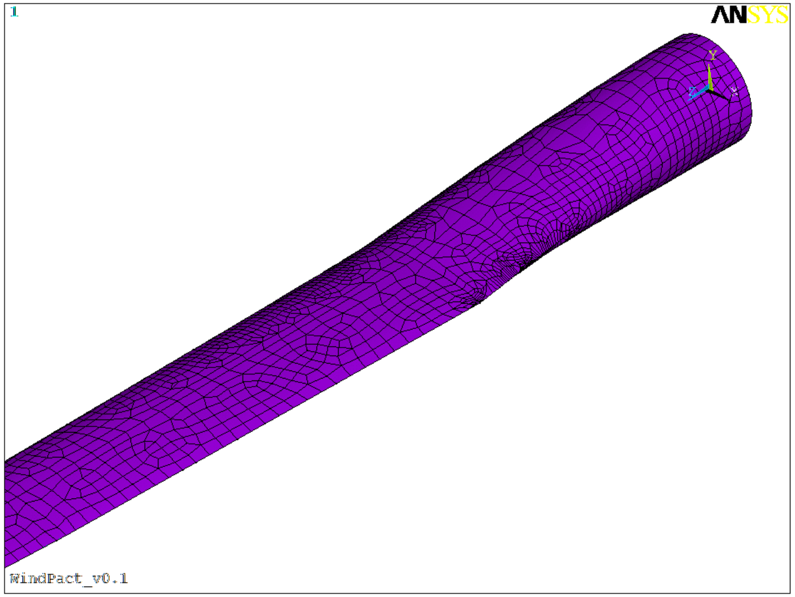
Explanation of 'shell7.src' commands (2)

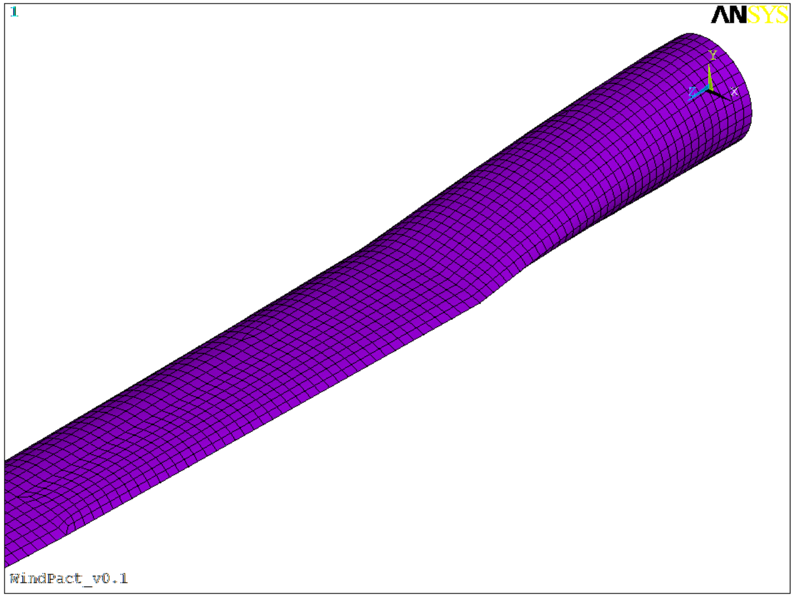
- Write material properties
- Define simulation title
- Define station keypoints and connect with lines
    - spline macros depending on 'TEType'
- Rotate keypoints according to blade twist
- Generate chordwise lines (HP and LP)
- Generate spanwise lines at LE and TE
- Create HP and LP areas
- Draw sapnwise lines on areas; lines connect material delineation points
- Clean up; combine lines
- Generate skin areas between lines
- Assign attributes to each area created; based on material assignments
- Create areas for shear webs and assign materials
- Mesh the model

Mesh – AESIZE vs Smart Size

- **There are two mesh options utilized by NuMAD:**

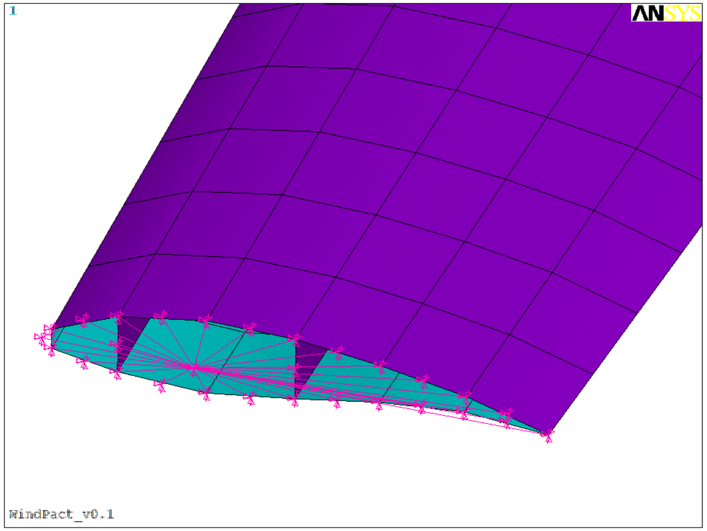
SMRTSIZE	AESIZE
Controls smart element size (fine-coarse)	Controls element size (meters)
Recommended in only special cases	Recommended for typical use





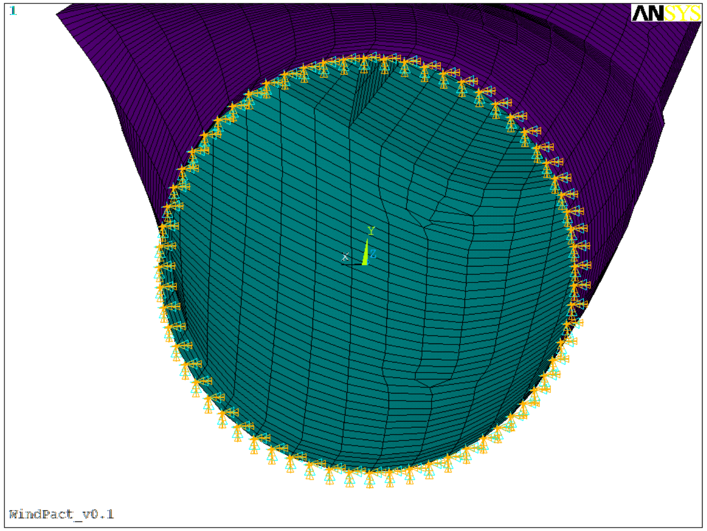
Explanation of 'shell7.src' commands (3)

- Create master node at blade tip



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

- (Optional: BPE instructions)



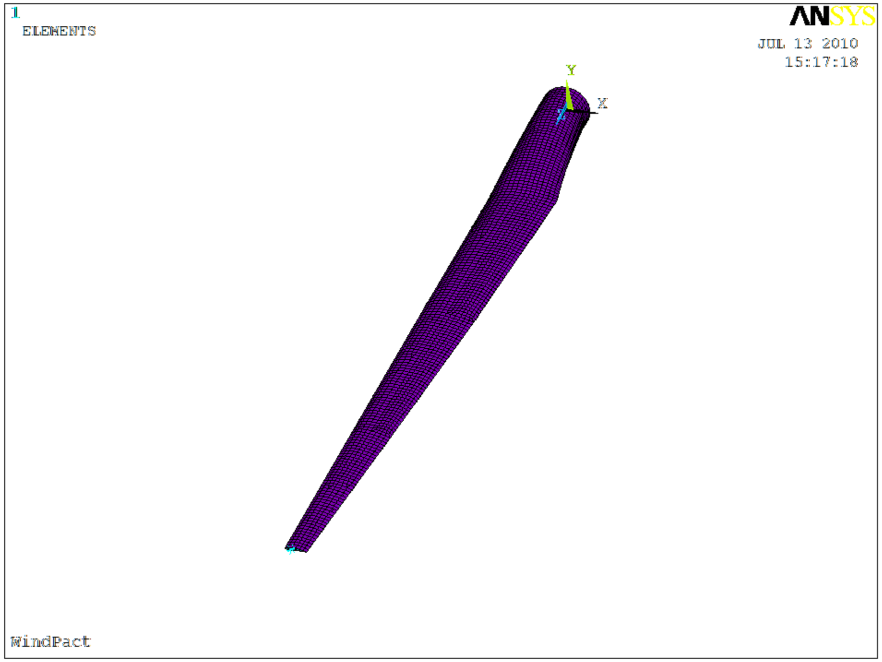
Exercise

- Generate the shell7 file for the NuMAD model

Shell7 generation

- **Start NuMAD**
- **Open blade project**
  - Ex5_FEModel\WP_Baseline
- **Set boundary conditions (cantilevered)**
- **Set element types (Shell281)**
- **Choose output types**
  - Shell7.src – yes
  - ANSYS *.db file – optional, depending on ANSYS status
- **Set mesh density**
  - Generate Model-> Mesh density: set to 0.2m

- **Generate files: Generate Model->Generate Now**
  - This process can take several minutes for a large model, be patient
- **Find the shell7.src file in the Blade Project folder**
- **(Optional) If you didn't choose to output the ANSYS .DB file, you may create the DB file from ANSYS using the /INPUT command**
  - /INPUT,shell7,src   (from the blade project directory)



Session 6

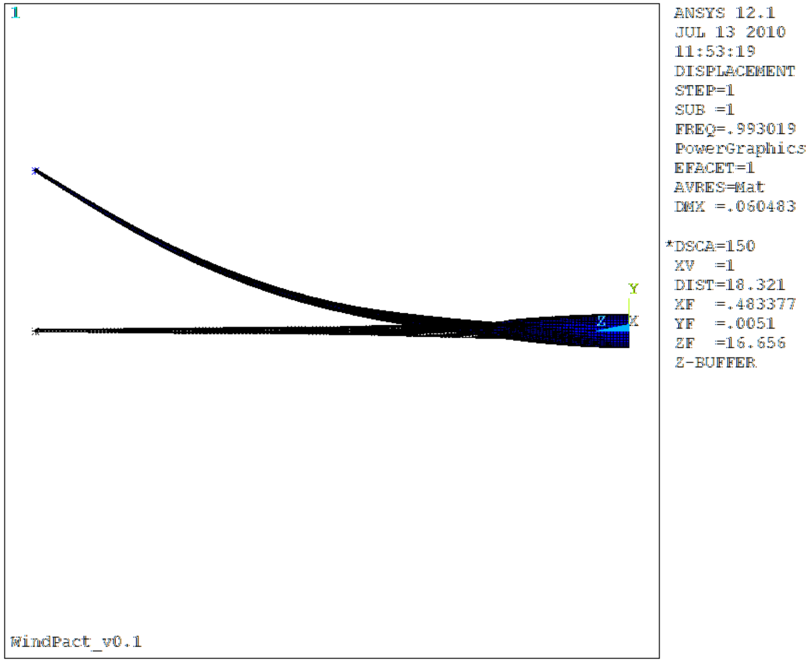
- **ANSYS blade analysis examples**
- **Goals:**
  - Provide commands for the most basic blade analyses in ANSYS
    - Modal
    - Static
    - Buckling
    - BPE

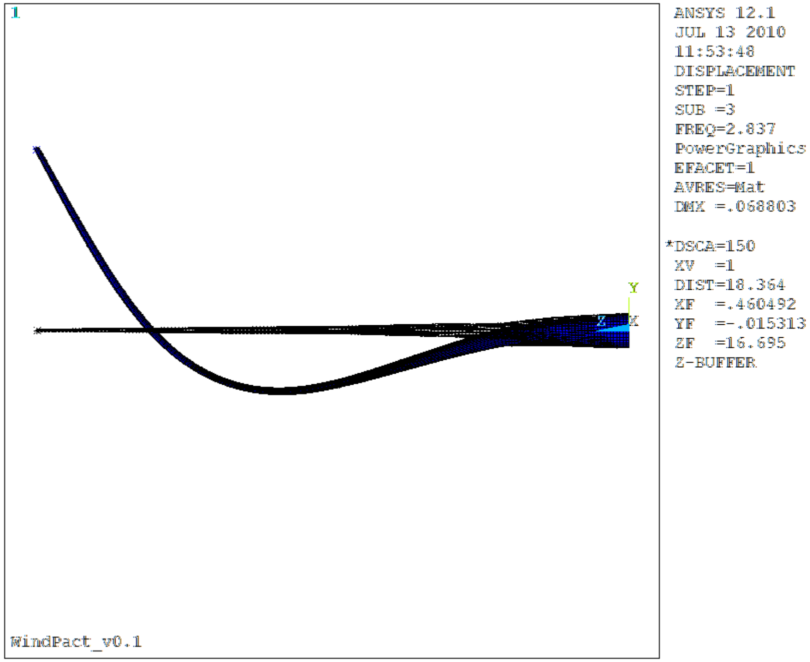
Modal

- Open *.db file in ANSYS
- Following is an example command sequence to find the first 6 modes:
  - /SOLU
  - ANTYPE,MODAL
  - MODOPT,LANB,6
  - SOLVE
  - FINISH
- Next, post processes the results. Use /DSCALE to exaggerate effects of the mode shape displacements, if necessary.
  - /POST1
  - SET,LIST
  - SET,1,SBSTEP (SBSTEP is the number of the substep – i.e. mode)
  - (/DSCALE,all,10 -- where 10 is a scale factor for displacement scaling)
  - PLDISP,1 (use zero instead of 1 to show no undeformed model outline)

Modal results

- **First flap mode**
- **Second flap mode**





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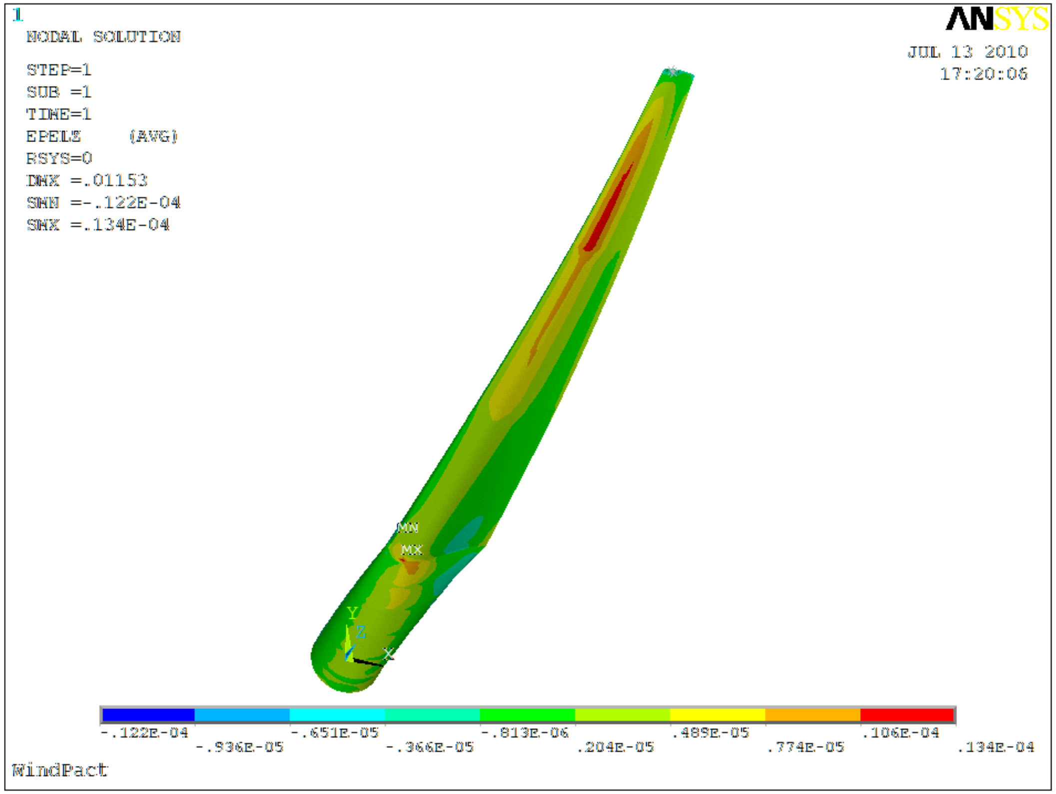
Static tip load

- **Open *.db file in ANSYS**
- **Following is an example command sequence for a static flapwise point load at the blade tip (on the master node)**
  - /SOLU
  - ANTYPE,STATIC
  - *GET,var,node,0,num,max   (finds the master node)
  - F,var,FY,100   (applies 100N to master node)
  - SOLVE
  - FINISH

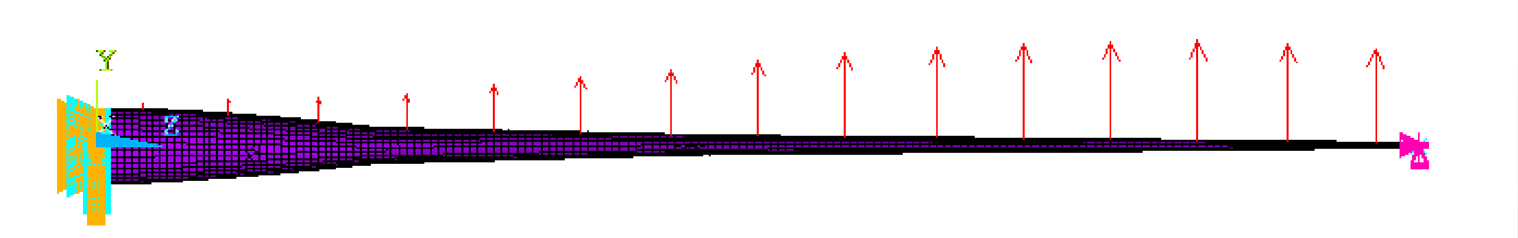
Static tip load results

- **Command sequence:**
  - /POST1
  - SET,1,1
  - PLNSOL,EPEL,Z
    - Plot spanwise elastic strain (z-direction)



Buckling

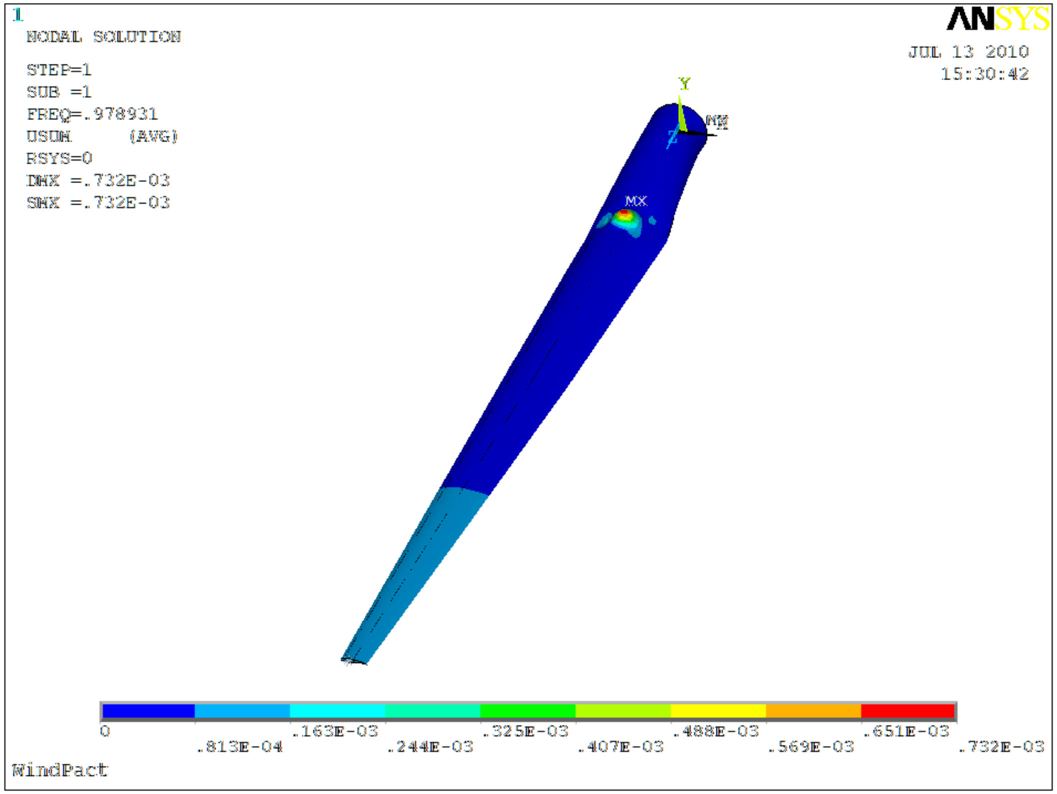
- **Use more realistic load distribution for this example. Forces are found in 'Ex6_Analyses\Aero_Forces' for models that have generated with 0.2m mesh size (AESIZE) for both SHELL99 and SHELL281 (Node numbering ends up slightly different in each case)**
- **Open the FE Model in ANSYS**
  - File location: Ex6_Analyses\FEM_Files\master.db
- **Apply forces to nodes (assuming meshed with shell281 elements)**
  - ANSYS command: /INPUT,forces281,txt



Buckling

- **Following is a command sequence to perform linear buckling analysis (assuming loads have been applied):**
  - /SOLU
  - ANTYPE,STATIC
  - PSTRES,ON
  - SOLVE
  - FINISH
  - /SOLU
  - ANTYPE,BUCKLE
  - BUCOPT,LANB,10
  - SOLVE
  - FINISH

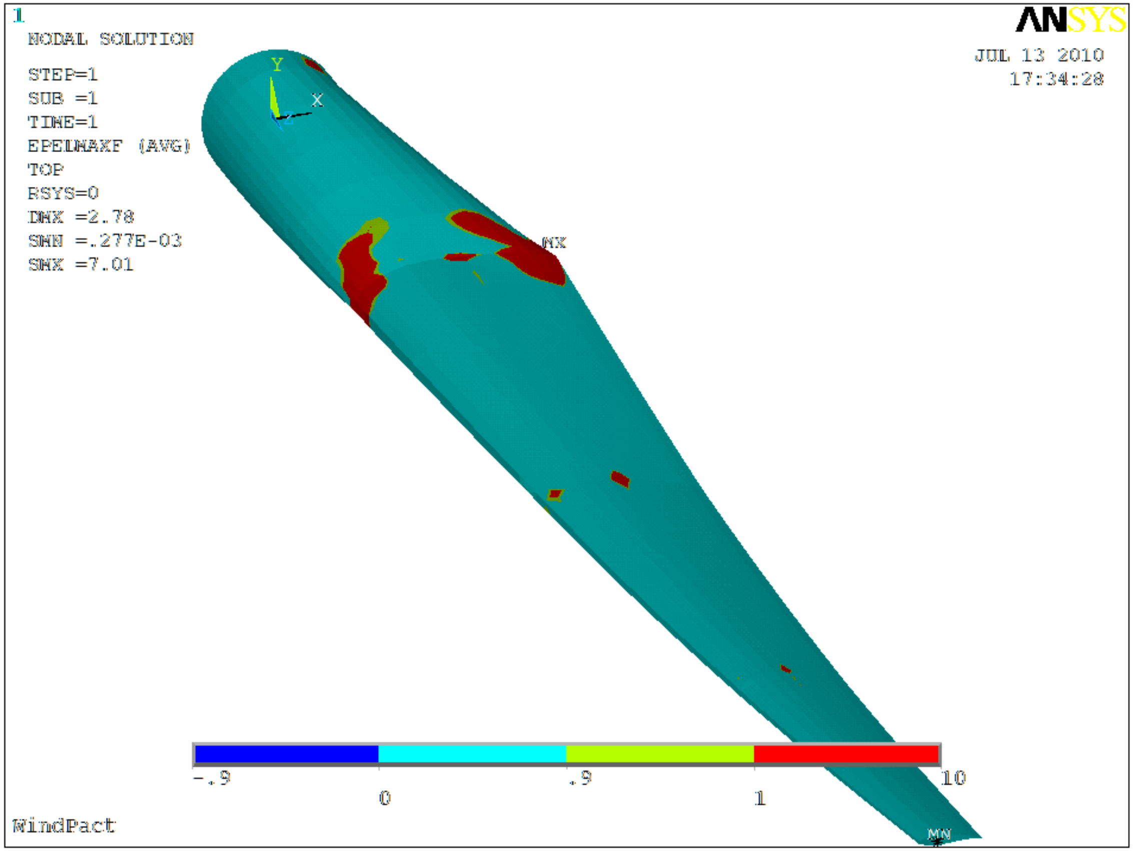
- **Buckling results analysis example**
  - /POST1
  - SET,1,1
  - /DSCALE,ALL,500
  - PLNSOL,U,SUM



- **Buckles at 0.9789 x Applied load…uh oh**

Static load failure criteria

- **Assume distributed load**
- **Assume failure at about 3500 microstrain, .35% strain (very conservative)**
- **Command ideas:**
  - Call FC.txt:
    - /INPUT,FC,txt
  - PLNSOL, FAIL, EMAX



Beam Property Extraction (BPE) in NuMAD

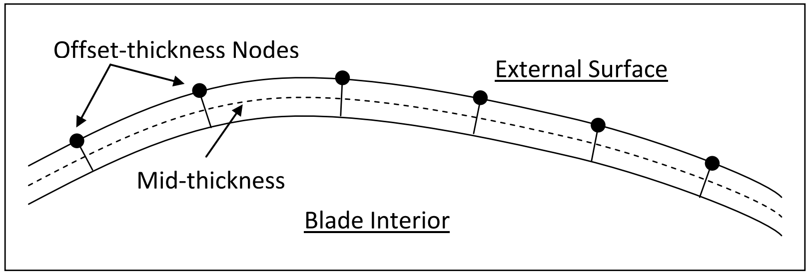
- **BPE in combination with NuMAD and ANSYS offer the ability to calculate and write distributed structural properties for direct use in the FAST full wind turbine aeroelastic simulation code**
  - FAST is available at the NREL NWTC Design Codes website: http://wind.nrel.gov/designcodes/simulators/fast/
  - Direct output of the *.dat “blade structure” file for FAST
    - Includes principle axes orientation, mass density, EI_flap, EI_edge and mode shapes
    - Currently does not write information that is not used by FAST; i.e. no GJ, EA, inertias, mass center, shear center, tension center, etc.

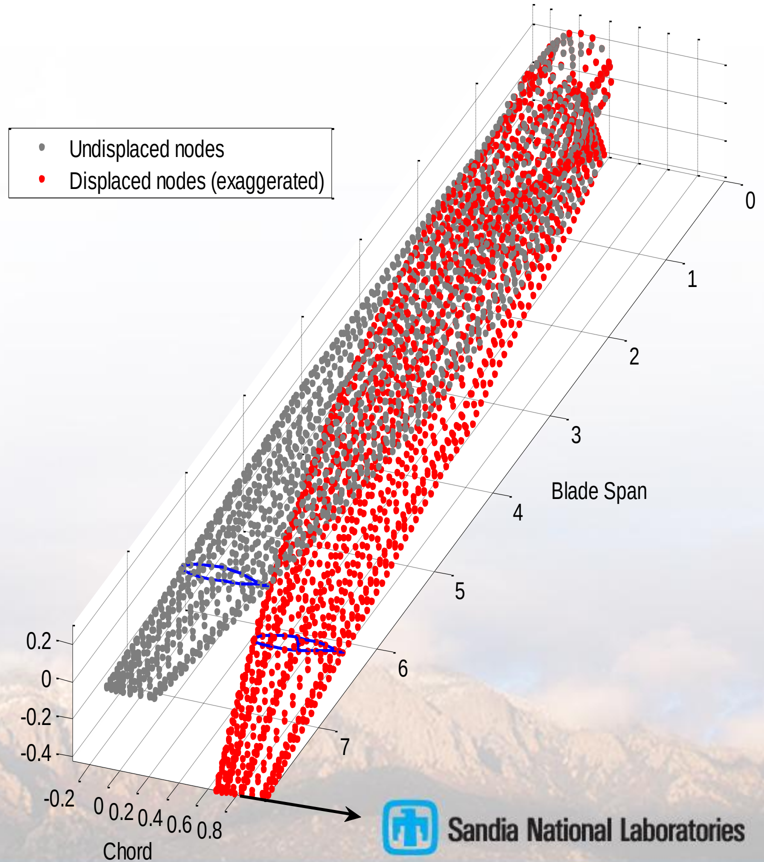
BPE background

- **References**
  - BPE development:
    - Malcolm, D. J. and Laird, D. L. "Extraction of Equivalent Beam Properties from Blade Models," *Wind Energy*, 2007, Vol. 10, pp. 135-137.
    - Malcolm, D. J. and Laird, D. L. "Identification and Use of Blade Physical Properties," *AIAA 43rd Aerospace Sciences Meeting and Exhibit*, 2005.
    - Malcolm, D. J. and Laird, D. L. "Modeling of Blades as Equivalent Beams for Aeroelastic Analysis," *AIAA 41st Aerospace Sciences Meeting and Exhibit*, 2003.
  - Practical usage examples:
    - Brian Resor, Joshua Paquette, Daniel Laird and D. Todd Griffith. "An Evaluation of Wind Turbine Blade Cross Section Analysis Techniques." *AIAA SDM Conference*. Orlando, FL. April 2010.

BPE full capability

- **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 (not all currently implemented in NuMAD…coming soon)**
- **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





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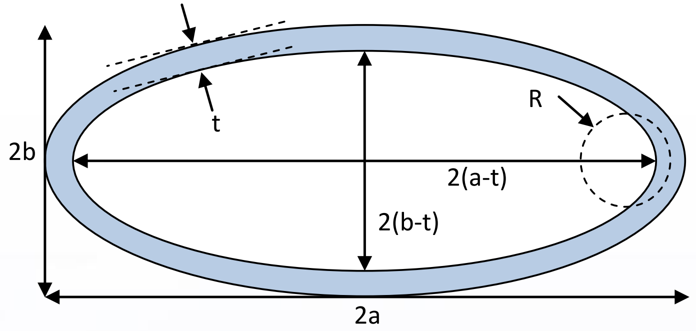
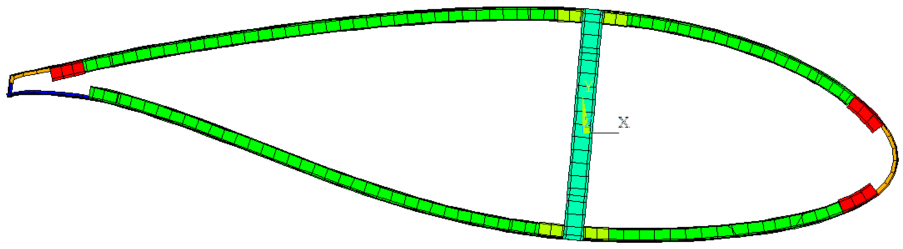
Verification shapes

- **2D & 3D properties compared to known properties (ANSYS Custom Section Tool)**





- **"Constant thickness ellipse"**
  - i.e. outer ellipse with constant wall thickness
  - Inner surface defined by an oval
- **Analytical solutions do not exist**
- **Known values determined using the ANSYS custom section analysis tool**
- **2a = 2meters**

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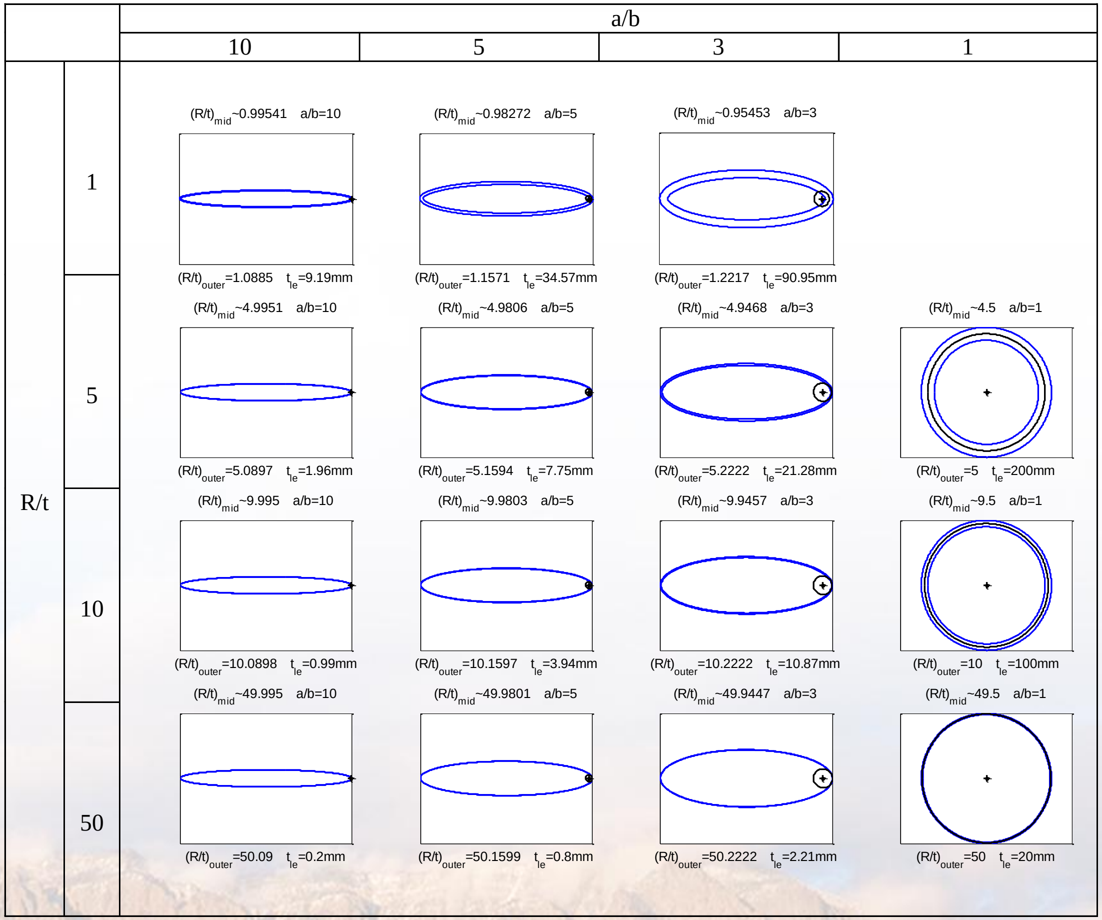
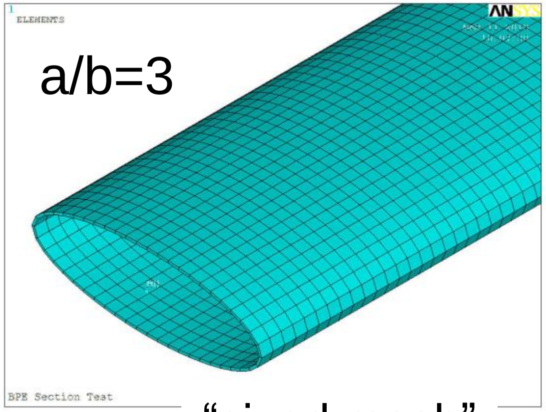
Parametric Cross Section Geometries

- **Ratio of leading edge curvature to thickness, R/t**
  - 1: Just above minimum allowable for shell elements
    - (R/t > 0.5 req'd)
  - 5: Recommended minimum for shell elements
  - 10
  - 50: Thin wall
- **Ratio of airfoil thickness to chord, a/b**
  - 10 (very thin airfoil)
  - 5
  - 3
  - 1 (cylinder)

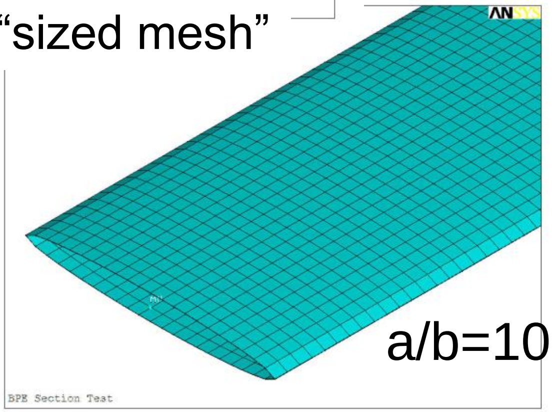


BPE checkout details

- ***Isotropic material only***
- **BPE**
  - Process:
    - Section shapes extruded to 40m
    - Boundary conditions: clamped on one end with unit load application on the other end (via rigid links)
    - EI & GJ vs span computed
    - Used values at mid-span to compute effective Ixx, Iyy and J
  - Mesh convergence results:
    - Any reasonable mesh size delivered good results
    - 0.1m Element size (with 2m chord)



“sized mesh”

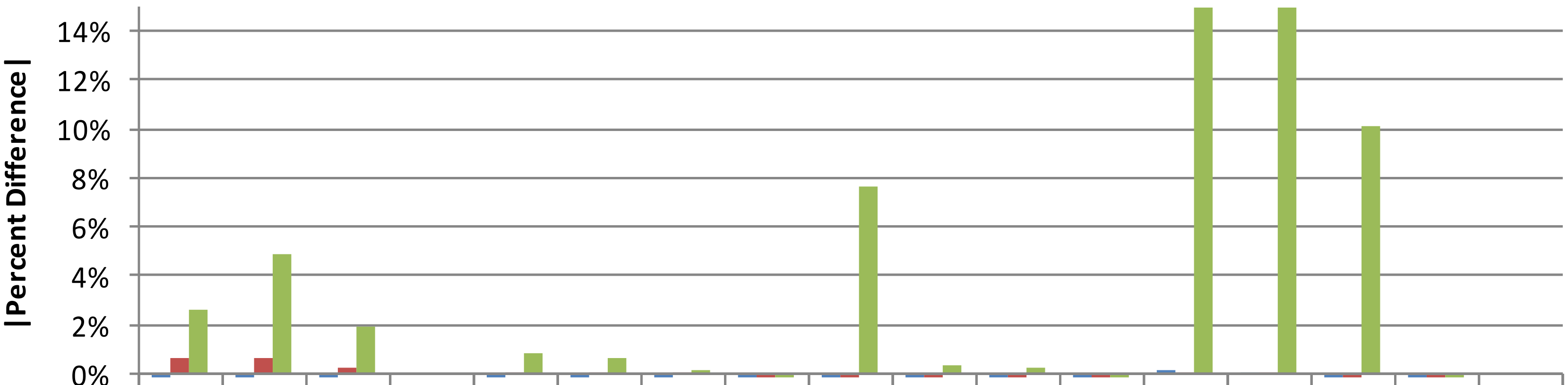


Constant thickness ellipse results

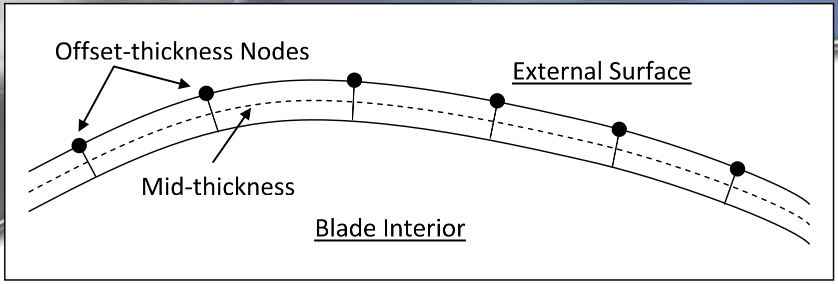
ANSYS & BPE

- Element used: Shell281, offset nodes, improved shell formulation
- Many discrepancies are very small, ~0.05%
- Warping effects obvious for higher a/b, especially thin skin (high R/t)

ANSYS R12, AESIZE=0.10, SHELL281, Offset Nodes, KEYOPT(2)=1



a/b	10	5	3	1	10	5	3	1	10	5	3	1	10	5	3	1
R/t	1	1	1	1	5	5	5	5	10	10	10	10	50	50	50	50
Iflap	0.01%	0.02%	0.02%		0.02%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.16%	0.10%	0.00%	0.00%
Iedge	0.70%	0.67%	0.30%		0.11%	0.07%	0.07%	0.01%	0.00%	0.01%	0.03%	0.00%	0.09%	0.14%	0.01%	0.00%
J	2.70%	4.92%	1.95%		0.92%	0.71%	0.24%	0.00%	7.75%	0.41%	0.35%	0.00%	31.47	22.09	10.18	0.00%



Improved shell formulation

ANSYS & BPE

New offset-node shell formulation

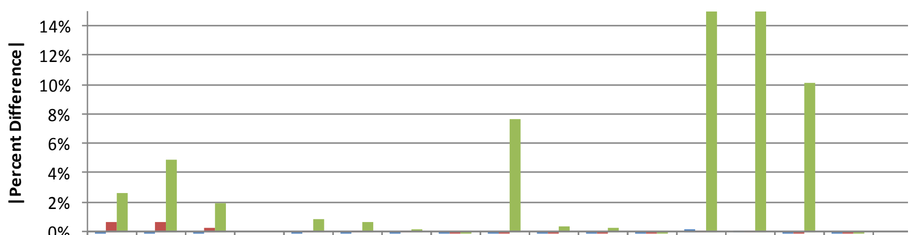
- Element used: Shell281, offset nodes, improved shell formulation
- Warping effects obvious for higher a/b, especially thin skin (high R/t)
- Many discrepancies are very small, ~0.05%

ANSYS & BPE

Historical offset-node shell formulation

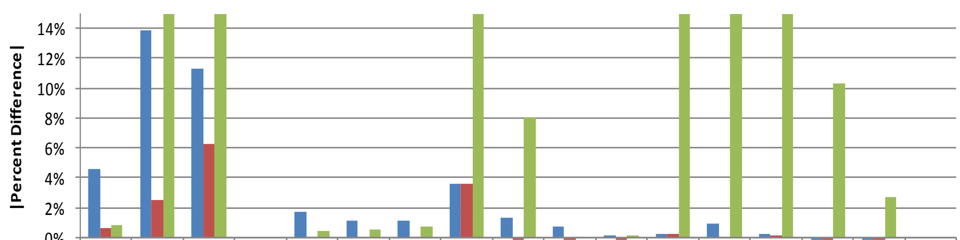
- In general, torsional stiffness is not represented accurately
- Discrepancies as high as 210%

ANSYS R12, AESIZE=0.10, SHELL281, Offset Nodes, KEYOPT(2)=1



a/b	10	5	3	1	10	5	3	1	10	5	3	1	10	5	3	1
R/t	1	1	1	1	5	5	5	5	10	10	10	10	50	50	50	50
Iflap	0.01%	0.02%	0.02%		0.02%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.16%	0.10%	0.00%	0.00%
Iedge	0.70%	0.67%	0.30%		0.11%	0.07%	0.07%	0.01%	0.00%	0.01%	0.03%	0.00%	0.09%	0.14%	0.01%	0.00%
J	2.70%	4.92%	1.95%		0.92%	0.71%	0.24%	0.00%	7.75%	0.41%	0.35%	0.00%	31.47	22.09	10.18	0.00%

ANSYS R11, AESIZE = 0.10, SHELL99, Offset Nodes



a/b	10	5	3	1	10	5	3	1	10	5	3	1	10	5	3	1
R/t	1	1	1	1	5	5	5	5	10	10	10	10	50	50	50	50
Iflap	4.68%	13.87%	11.40%		1.78%	1.15%	1.15%	3.61%	1.39%	0.77%	0.21%	0.30%	0.99%	0.27%	0.05%	0.01%
Iedge	0.73%	2.53%	6.34%		0.10%	0.10%	0.14%	3.61%	0.01%	0.02%	0.05%	0.30%	0.08%	0.18%	0.01%	0.01%
J	0.86%	40.43%	209.98		0.44%	0.62%	0.82%	33.74%	8.13%	0.09%	0.22%	26.05%	31.47%	22.14%	10.32%	2.74%

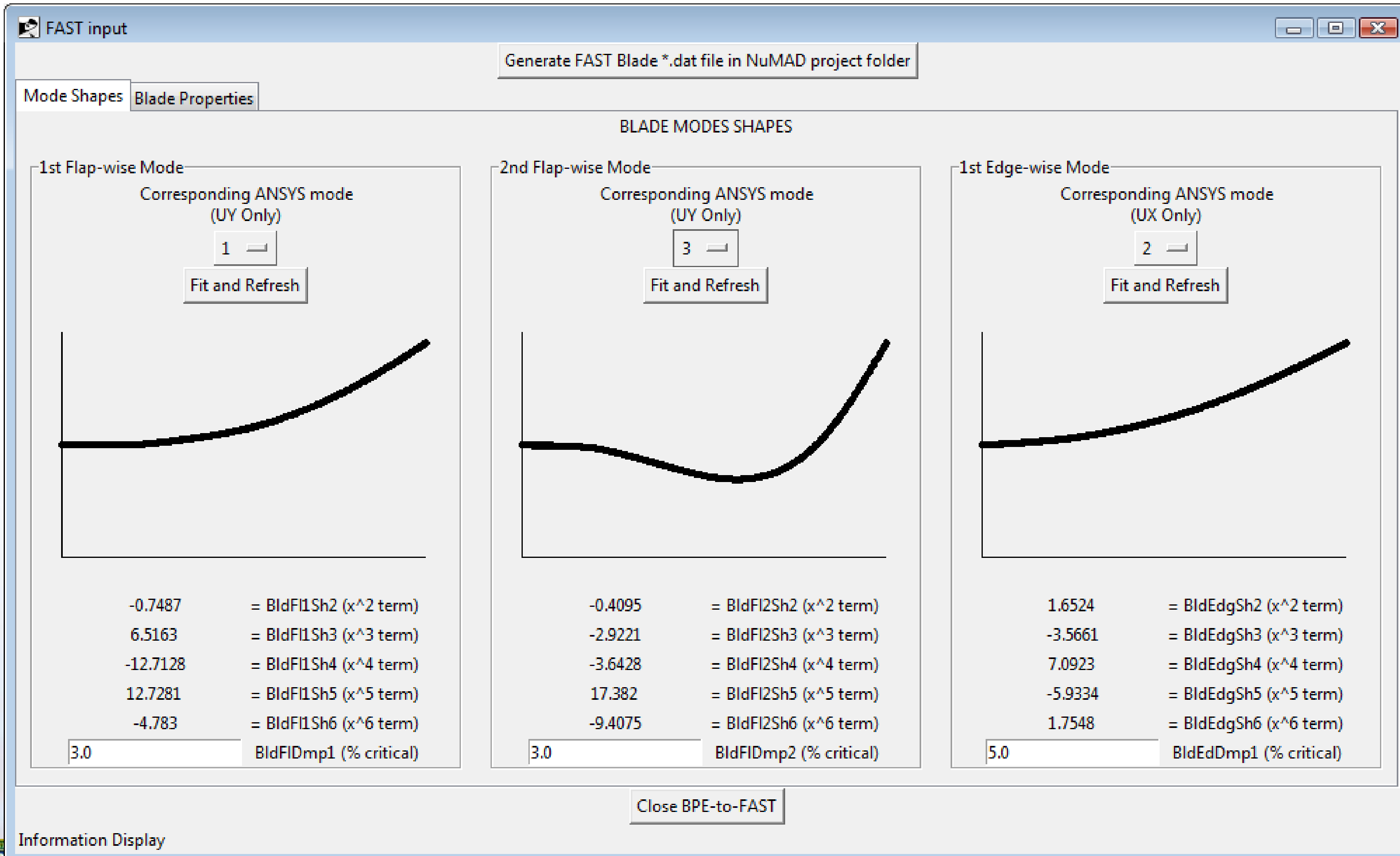
BPE - Files and directory structure

- **BPE files**
  - NuMAD\Ncore\bpeLibs
  - If this directory is missing, then you need to get the latest NuMAD distributable which includes BPE files
  - BPE consists of compiled Matlab scripts and requires supporting files for standalone use
- **Output files**
  - **ProjectFolder**
    - **BPE2FAST_Blade.dat – FAST blade file**
  - **ProjectFolder\BPE**
    - **Miscellaneous intermediate BPE files**

Perform BPE analysis from NuMAD

- **Start with the NuMAD model found in the following location**
  - Ex6_Analyses\NuMAD_and_BPE\WP_Blade
- **Set Output to**
  - Shell7 – yes
  - ANSYS db – yes
  - FAST Input -> Set Beam Elements
    - Choose all stations to serve as BPE node locations
  - Generate Model-> Generate Now
    - Generates shell7.src
    - Generates master.db
    - Performs all BPE runs (6 static loads and 1 modal)

BPE results in NuMAD



BPE results in NuMAD

FAST input

Generate FAST Blade *.dat file in NuMAD project folder

Mode Shapes | Blade Properties

DISTRIBUTED BLADE PROPERTIES

BlFract	AeroCent (-)	StrcTwst (deg)	BMassDens (kg/m)	FlpStff (N-m^2)	EdgStff (N-m^2)
0	0	4.00141	158.314	1.34859e+009	1.16474e+009
0.0105263	0	6.7462	163.014	1.16946e+009	1.17935e+009
0.04	0.02	14.4316	176.175	6.67894e+008	1.22026e+009
0.0778947	0.0513	14.4994	177.802	4.74545e+008	1.35391e+009
0.115789	0.0739	15.2655	177.651	3.23414e+008	1.38861e+009
0.153684	0.0965	14.1517	176.881	2.41584e+008	1.38044e+009
0.191579	0.1104	10.4359	177.294	8.39986e+007	4.85129e+008
0.342105	0.1275	12.9864	246.199	1.74119e+008	5.04199e+008
0.605263	0.157	5.4771	100.922	2.98027e+007	1.55177e+008
0.868421	0.186	-12.7109	45.2674	3.69979e+006	2.16019e+007
1	0.2	-21.8049	17.44	3.69979e+006	2.16019e+007

Close BPE-to-FAST

Information Display

BPE future work

A future release of NuMAD will include the ability to output many more section properties from the BPE analysis:

- EI_flap
- EI_edge
- EA
- GJ
- Flap_inertia
- Edge_inertia
- Tension center
- Shear center
- Center of gravity
- Mass density
- Coupled stiffnesses
- Bend-twist coupling coefficient
- Full 6x6 Timoshenko stiffness matrices

Session 7

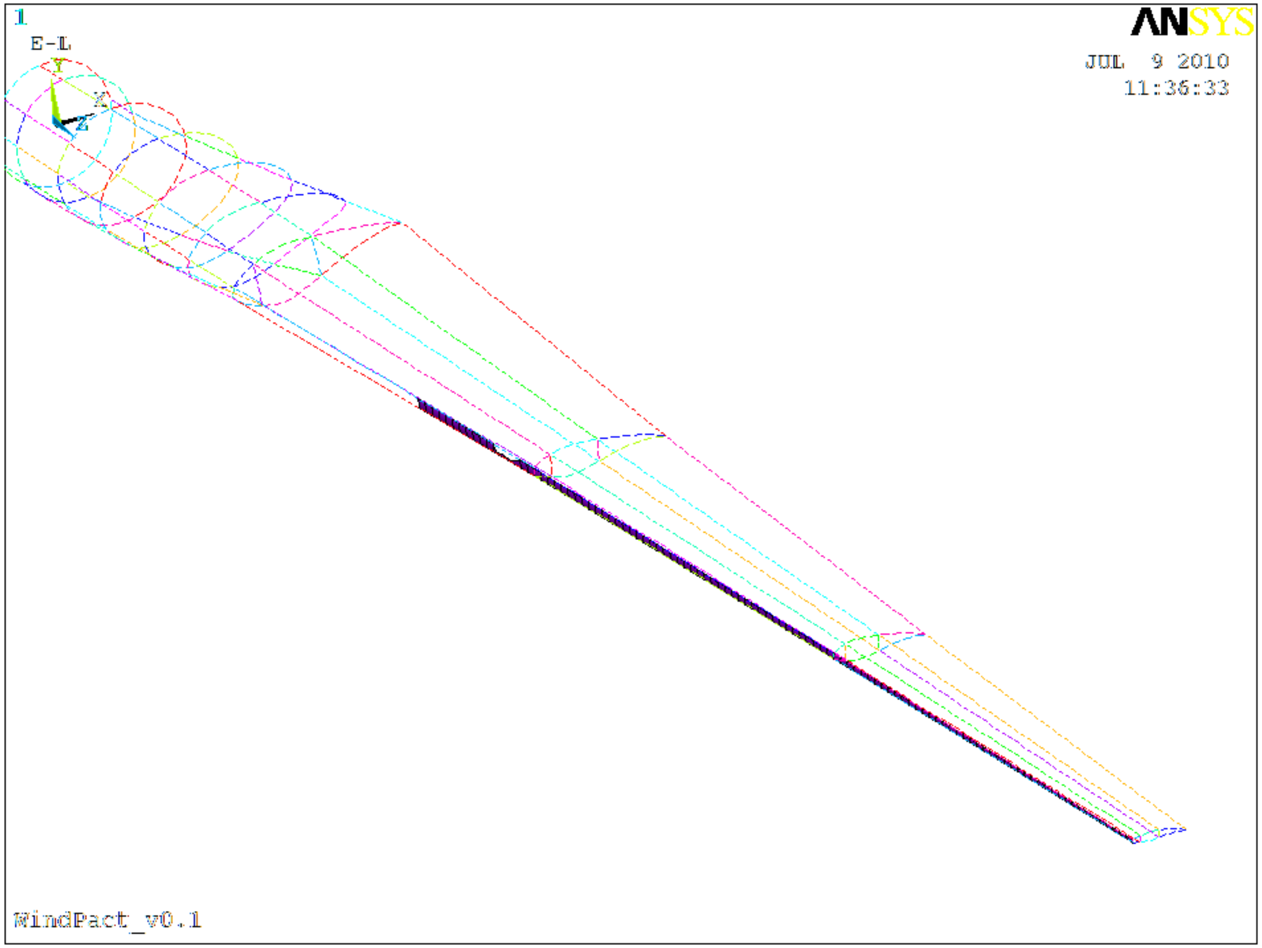
- **Improvements to WP blade design and FE modeling nuances**
- **Goals:**
  - Discuss blade design methodologies

Nuances of model creation

- **Station interpolation**
- **Material delineation points management**
  - Recommend to minimize use of transistion DP’s (flares, hourglass, doubles)
  - These features are intended for modeling actual triangular material placements, not for consolidation of DP’s along span of the blade
- **Shear web entry**
  - Recommend not to add shear web until all DPs are in place
- **Use of x10 materials**

Use of x10 materials

- ANSYS: CHECK,ESEL,WARN & Multiplot (lines and elements) reveals the following elements with high thickness/curvature:



Sharing NuMAD models

- **Best bet: Share entire project directories and Ncore directory**
- **When space is limited following are the required files:**
  - Airfoils/<all contents>
  - MatDBsi.txt
  - Sdata1.nmd
  - Sdata3.nmd
  - Optional: *.mac (zAirfoil, Flatback, Smoothe)

How to build a better 34m blade

Strength and/or buckling resistance

- Thicker root skin?
- More plies in the max chord region?
- Include core inboard of max chord?
- Better shape transition around max chord?
- Start shear web inboard of 25% span?

Reduce weight

- Terminate shear web somewhere short of the blade tip?
- Look for opportunity to loose material?
- Include carbon in spar cap mix and near root?

Exercise – Blade improvement

- **Shear web inboard of 25% span**
- **Begin with baseline NuMAD model and extend the shear web inboard beyond 25% span**
  - Material DPs for shear web installation at stations listed in Table below
  - Use WindPact_SW_25 for composite stack of additional shear web

Station #	Distance from root (m)	Front SW DP location (% chord)	Aft SW DP location (% chord)
5	4.48	19.621	62.506
6	5.74	17.428	56.096

Improvement Results

- **There are extremely beneficial improvements that can be done for very little weight:**

design	flapwise point load at blade tip to buckle (N)	increase from baseline	overall model mass (kg)	increase from baseline
Baseline: Shear web begins at 7m	41,550	--	4665	--
Modified: Shear web begins farther inboard at 4.48m	59,063	42%	4697	0.7%

- **…Possibilities are endless for improving this blade design. Use it to gain understanding and intuition whenever possible.**

The End

Thanks for your attendance!

Contents of Example Files

Example	Model begin point	Model end point
Files and directory structure (Airfoils)	NuMAD distributable	Addition of single airfoil file
Blade geometry setup	NuMAD distributable	Blade skins composed of 5mm steel
Materials setup	Blade skins composed of 5mm steel	Steel skins; materials and stacks entered into database
Materials assignment	Steel skins with materials; some materials defined in root region	Shear webs added; Materials assigned; baseline NuMAD model finished
FE model creation	Shear webs added; Materials assigned; baseline NuMAD model finished	(shell7 file created; ANSYS DB file created)
Analysis examples	Aero_Forces: commands for application of load to blade FEM_Files: shell7.src and ANSYS DB file NuMAD_and_BPE: Finished model; ready for BPE analysis in ANSYS	--
Blade design improvements	Baseline: Baseline FE Model Files With_SW_Extension: Baseline model with SW modification for increased buckling resistance Station_data.xls: Excel file containing DP locations for extending the SW inboard	--