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Mapping of 1D Beam Loads to the 3D Wind Blade for Buckling Analysis

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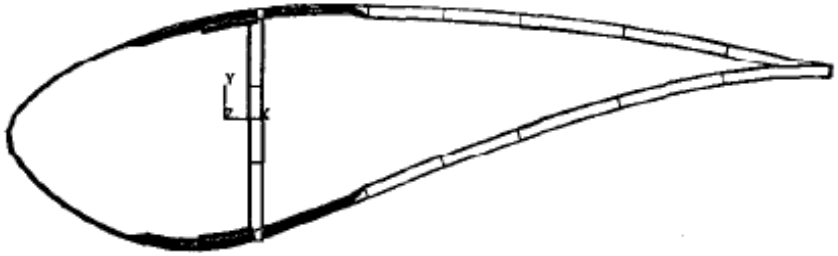
Introduction



- **Wind turbine blade design**
  - Spar caps are designed to carry majority of the load
  - Shear webs support the shell structure, transferring load between skins
  - Unsupported skin panels may buckle in compression. *Buckling load is an important design load case.*
- **Considerations in Buckling Load calculation**
  - FE blade model: element type, mesh size, material layup
  - Load definition: point load, line load, pressure distribution
  - Linear and non-linear buckling

Buckling and CFD Pressure Distribution

- Liu, W., Ma, Y., Su, X., and Huang, K., "Buckling Analysis of Wind Turbine Blade Using Pressure Distributions Obtained from CFD," *Power and Energy Engineering Conference*, APPEEC, 2009.
- Number of CFD grids was an order of magnitude greater than number of shell elements
- In our present work, we did not consider CFD pressure distribution, but we may in future work

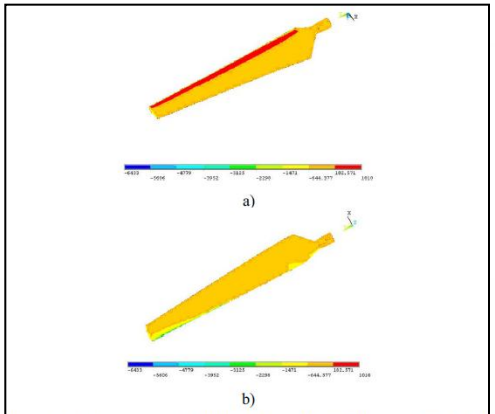


Figure 3. The pressure distribution obtained from CFD calculation(wind speed: 15m/s), a) upper surface; b) lower surface.

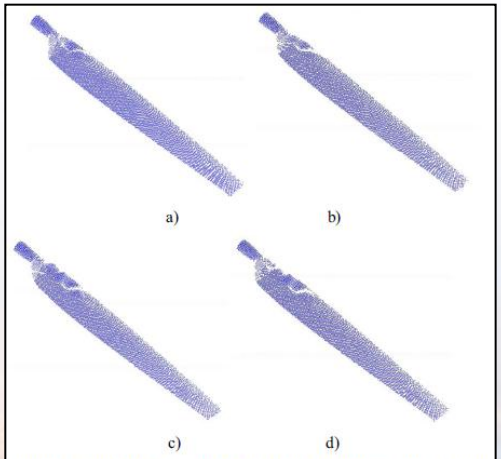


Figure 5. Buckling shapes of the first 4 buckling modes. a) 1st; b) 2nd; c) 3rd; d) 4th. Wind speed: 15m/s

Motivation

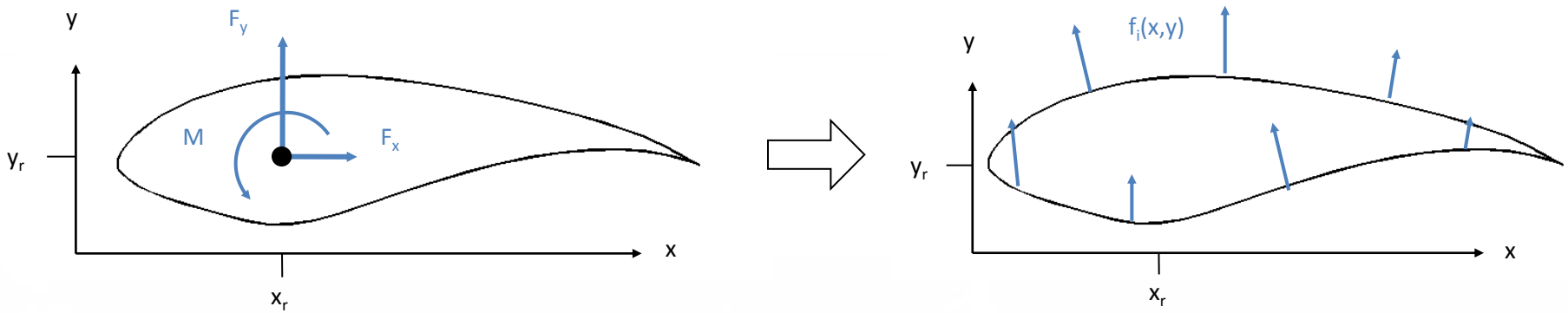
- **Although CFD pressure distribution is the closest to reality, the blade designer needs tools which can do iterations quickly**
- **Aeroelastic model of the wind blade is generally reduced down to a simple beam model for computational efficiency**
  - The aerodynamic loading typically consists of two forces and a moment applied at the center of each beam element in the one-dimensional beam
  - Can anything be gained by mapping the line of point loads to a “pressure-like” distribution?

Objective

- **Task 1: Develop a consistent methodology for mapping one-dimensional distributed beam loads to a three-dimensional shell structure**
- **Task 2: Apply the mapping technique to the panel buckling problem, comparing with other simplified methods of defining the load**

- **Why buckling analysis?**
  - We suspect that buckling could be sensitive to the distribution of forces over the skin.

Load Mapping



We require static equivalence:

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

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

We assume linear spatial distribution:

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

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

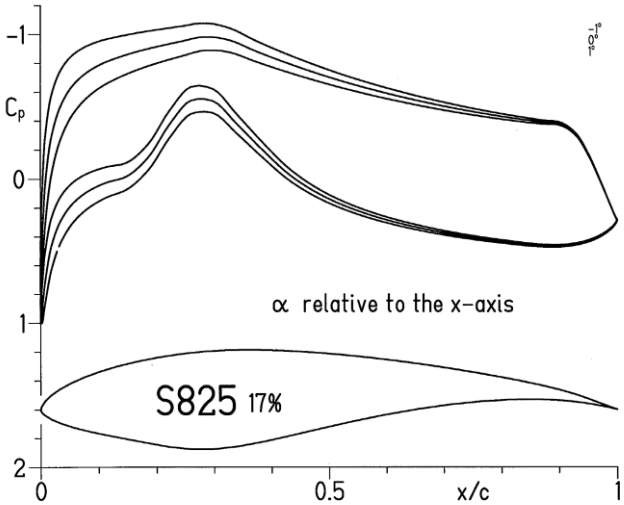
$$M = \sum_{i=1}^{N} (x_i - x_r) \cdot f_{y,i} \qquad 0 = \sum_{i=1}^{N} -(y_i - y_r) \cdot f_{x,i}$$

Load Mapping Solution

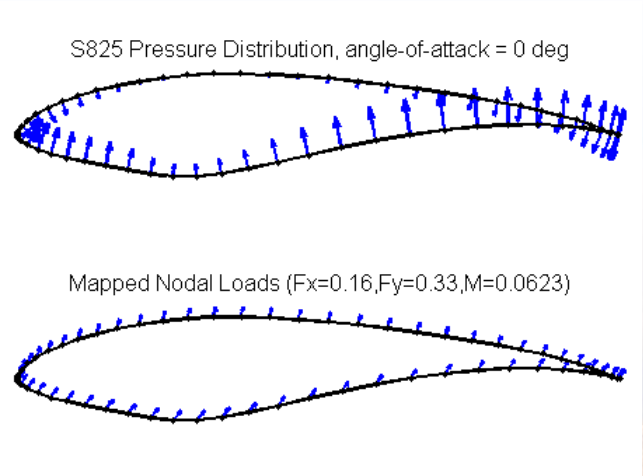
$$\begin{bmatrix} m_y & 1 & 0 & 0 \\ 0 & 0 & m_x & 1 \\ 0 & 0 & m_{xx} & m_x \\ -m_{yy} & -m_y & 0 & 0 \end{bmatrix} \begin{Bmatrix} a_x \\ b_x \\ a_y \\ b_y \end{Bmatrix} = \begin{bmatrix} F_x/N \\ F_y/N \\ M/N \\ 0 \end{bmatrix}$$

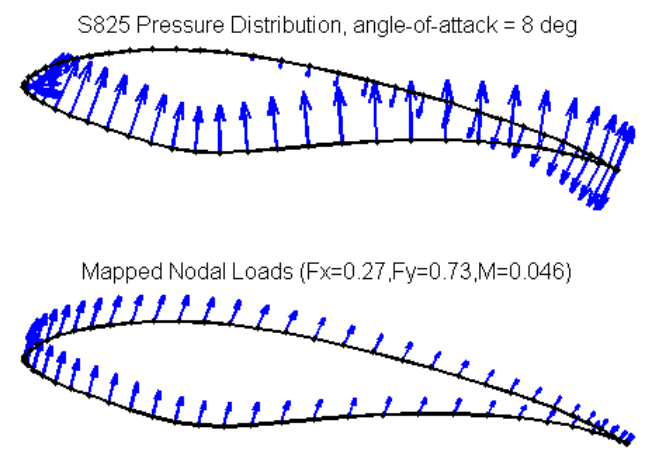
$$m_x = \text{mean}(x_i - x_r) \qquad m_{xx} = \text{mean}\left((x_i - x_r)^2\right)$$

$$m_y = \text{mean}(y_i - y_r) \qquad m_{yy} = \text{mean}\left((y_i - y_r)^2\right)$$



(1)

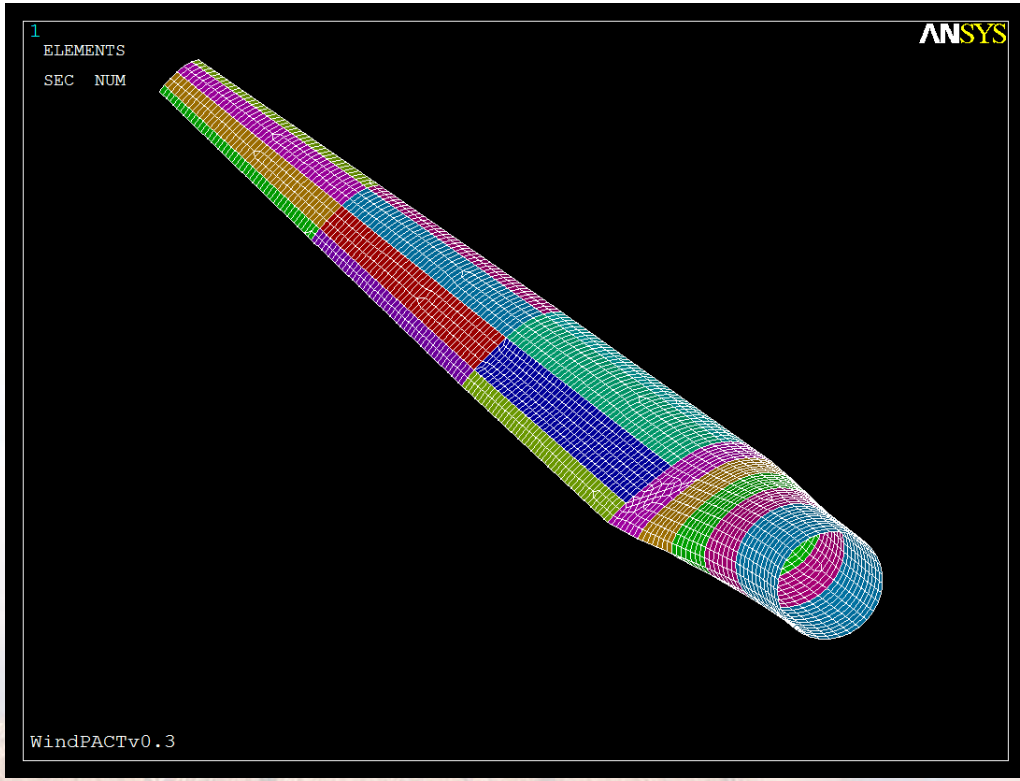




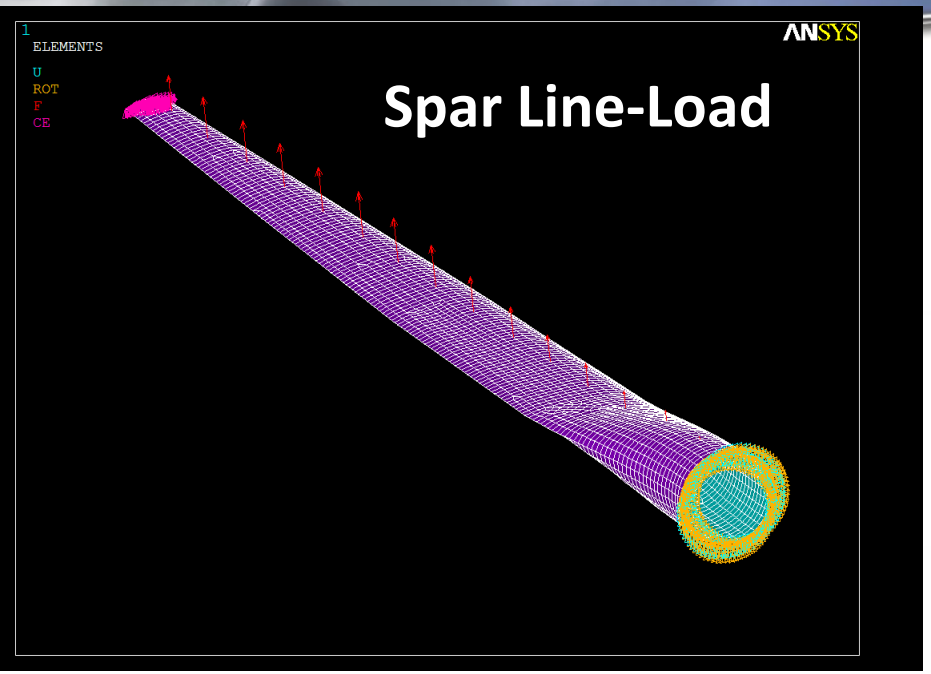
(1) Somers, D.M., "The S825 and S826 Airfoils," NREL Contractor Report NREL/SR-500-36344, January 2005.

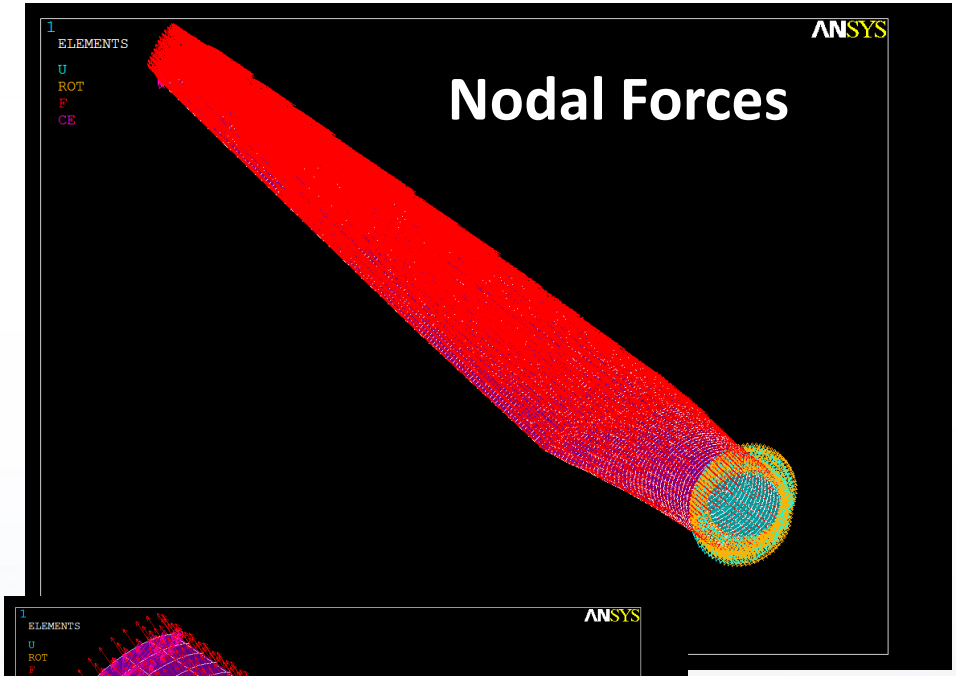
Blade Model

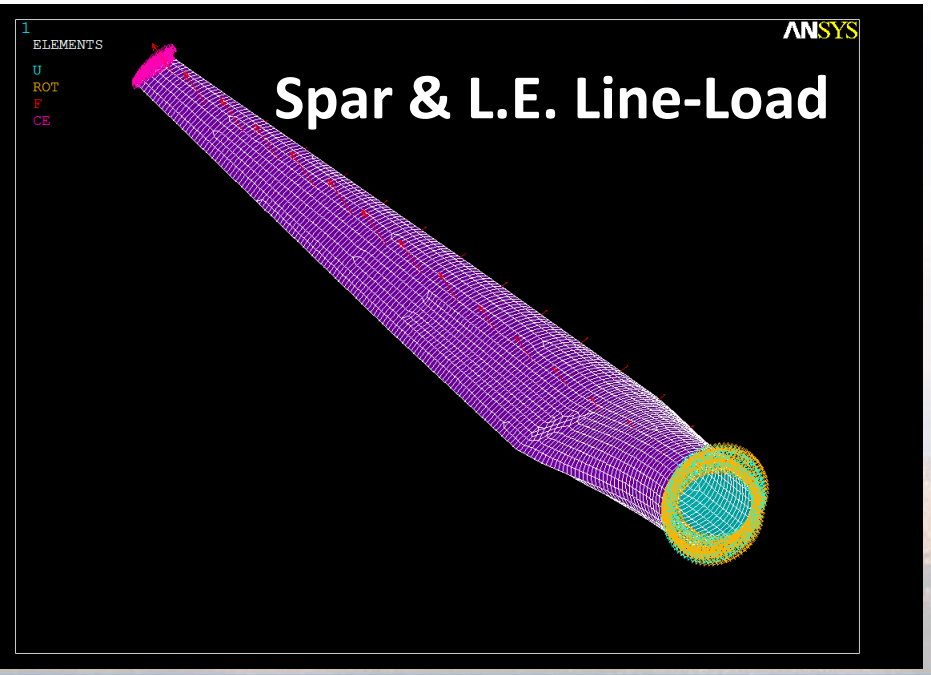
- **Sandia Labs has developed a NuMAD model of the WindPACT 1.5MW blade design**
- **For this work:**
  - 5,178 SHELL281 elements
  - 14,966 nodes
- **Blade loads taken from simulation at rated wind speed of 12 m/s**

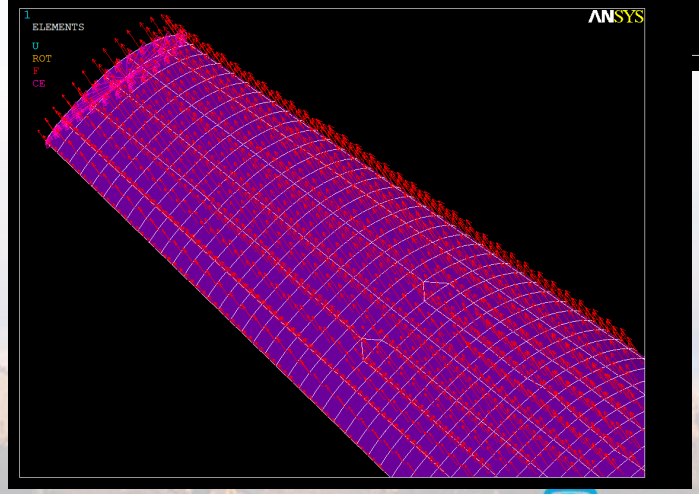


Loading Approaches

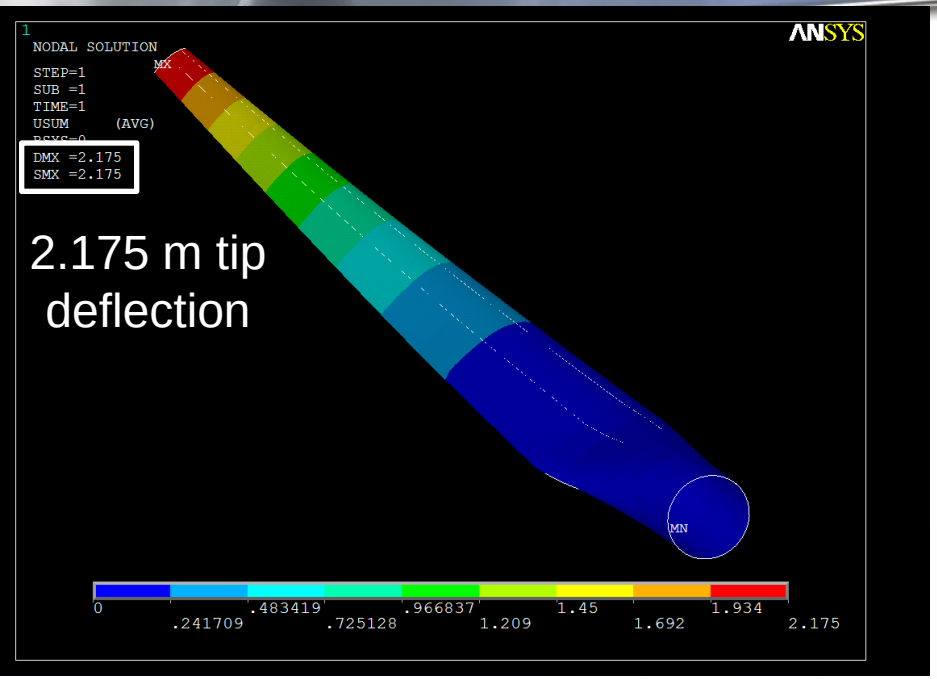




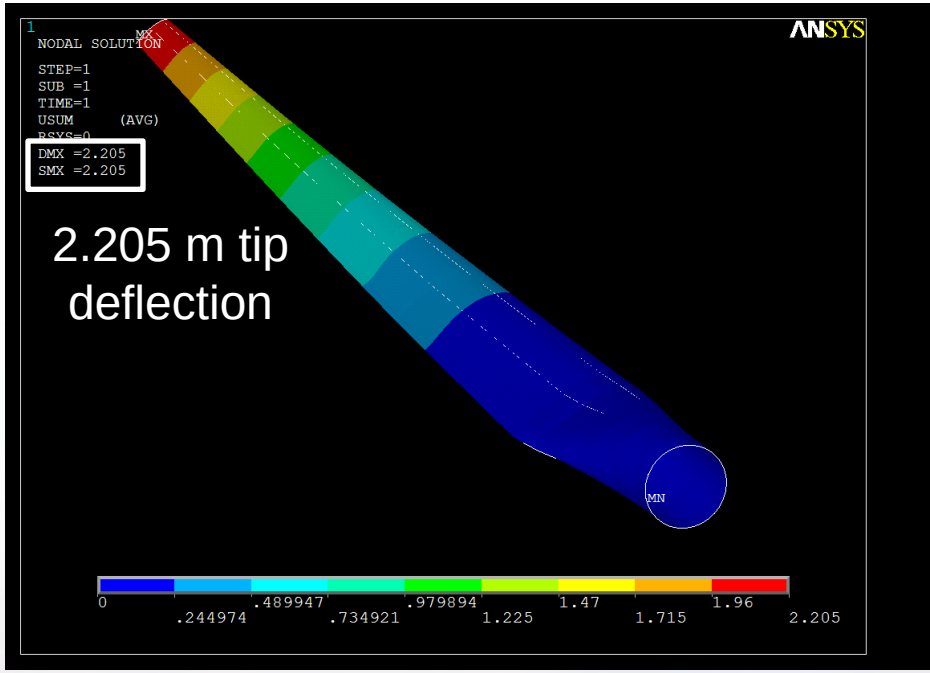




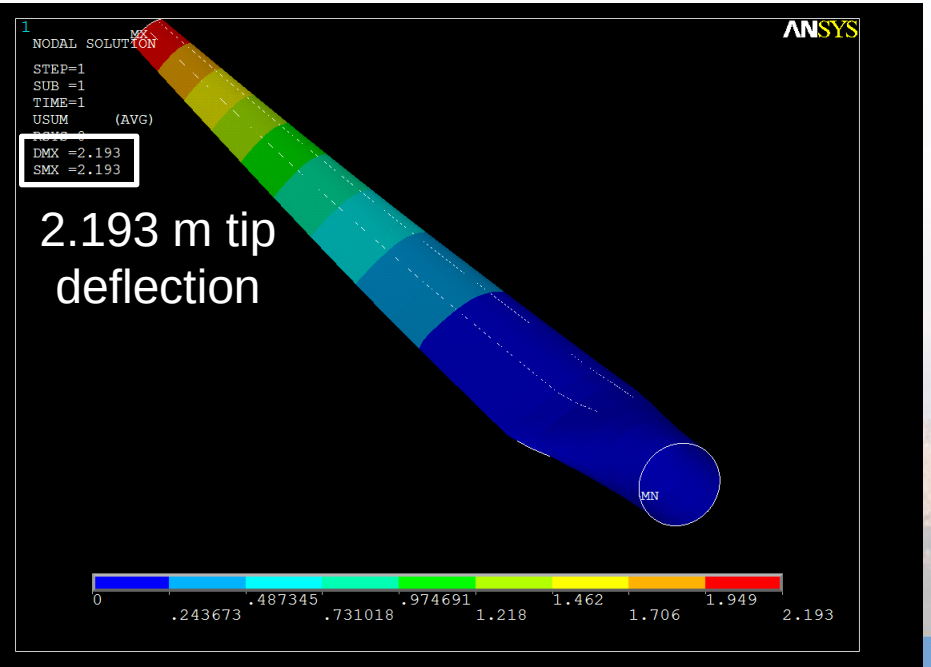
Static Analysis: Deflected Shape



2.175 m tip deflection

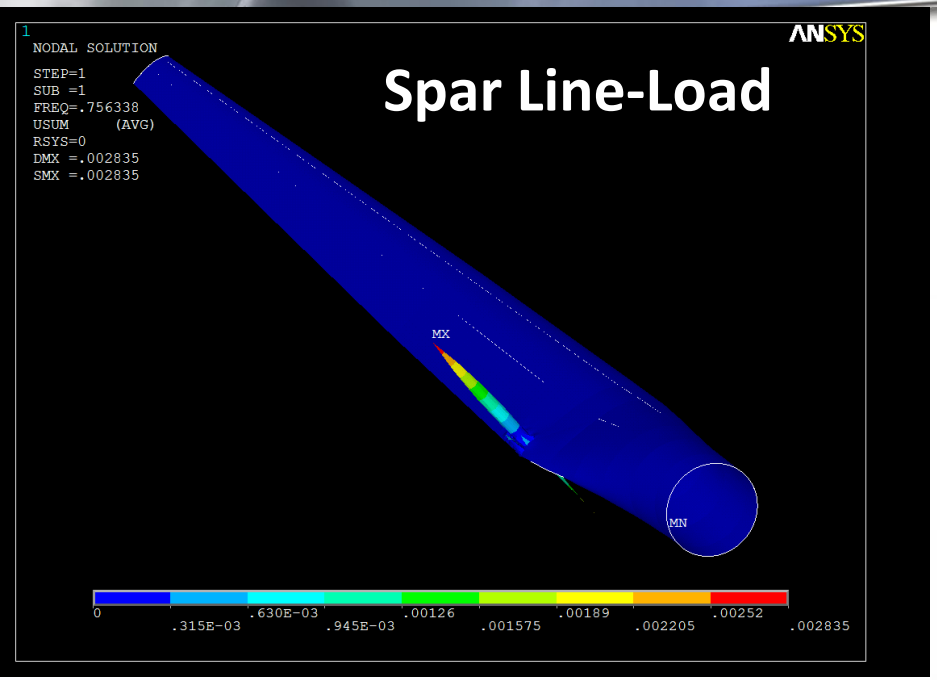


2.205 m tip deflection

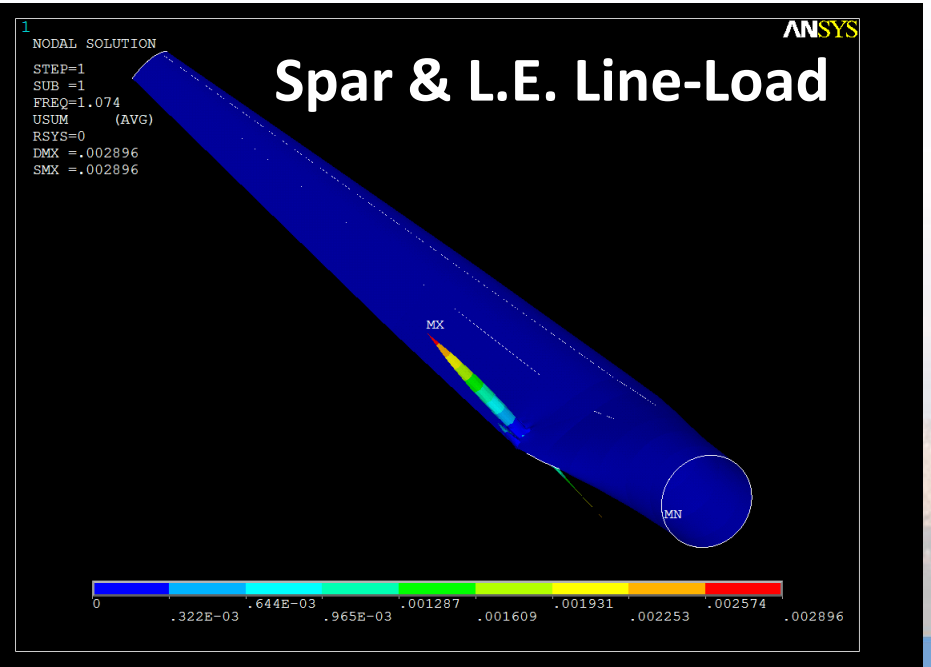


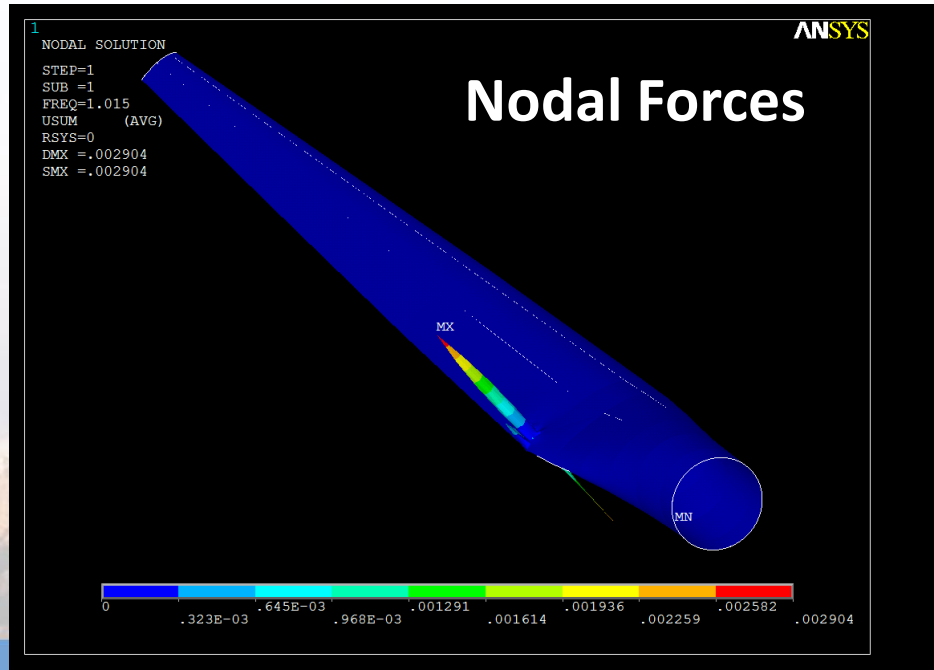
2.193 m tip deflection

Eigen (Linear) Buckling Analysis



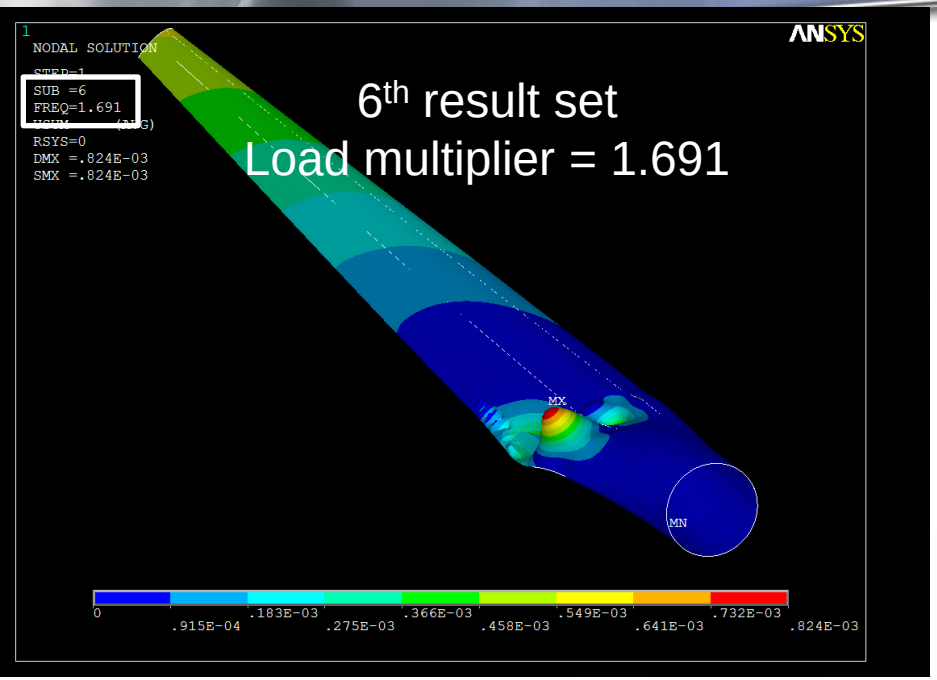
- In all three approaches, some modes are spurious
- Indicates problems with trailing edge elements

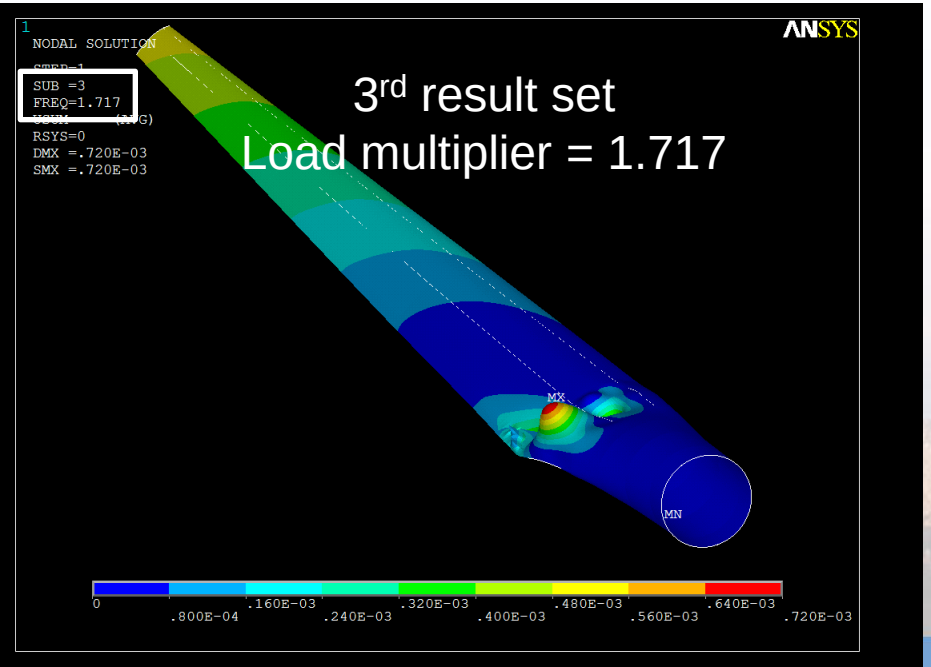


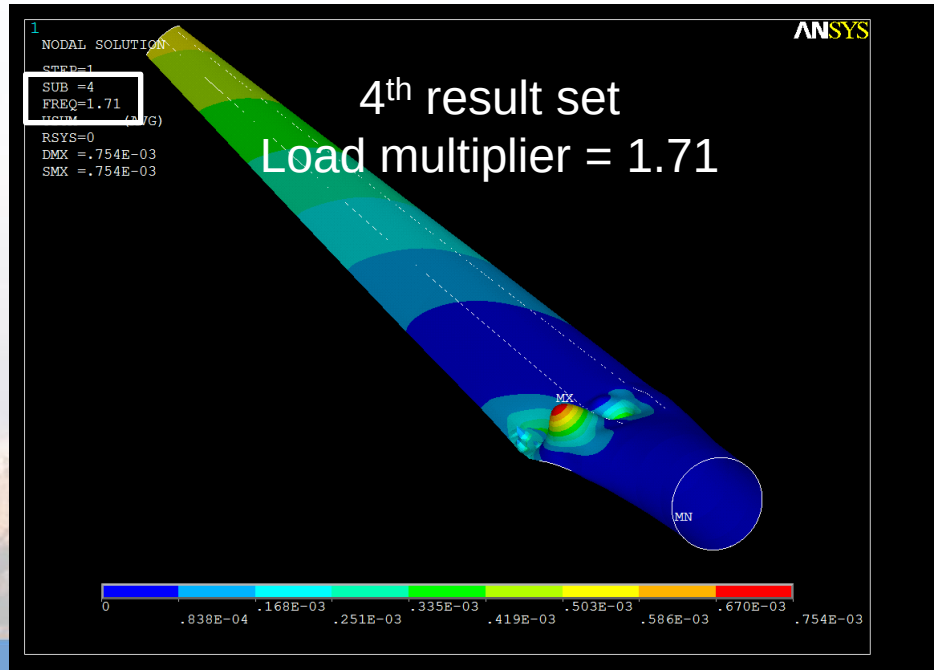


Eigen Buckling Analysis

- **First real buckling mode has Load Multiplier of 1.7**
- **The approaches produce similar buckling shapes**
- **The Line-Load has more spurious modes (6th result vs. 3rd/4th)**

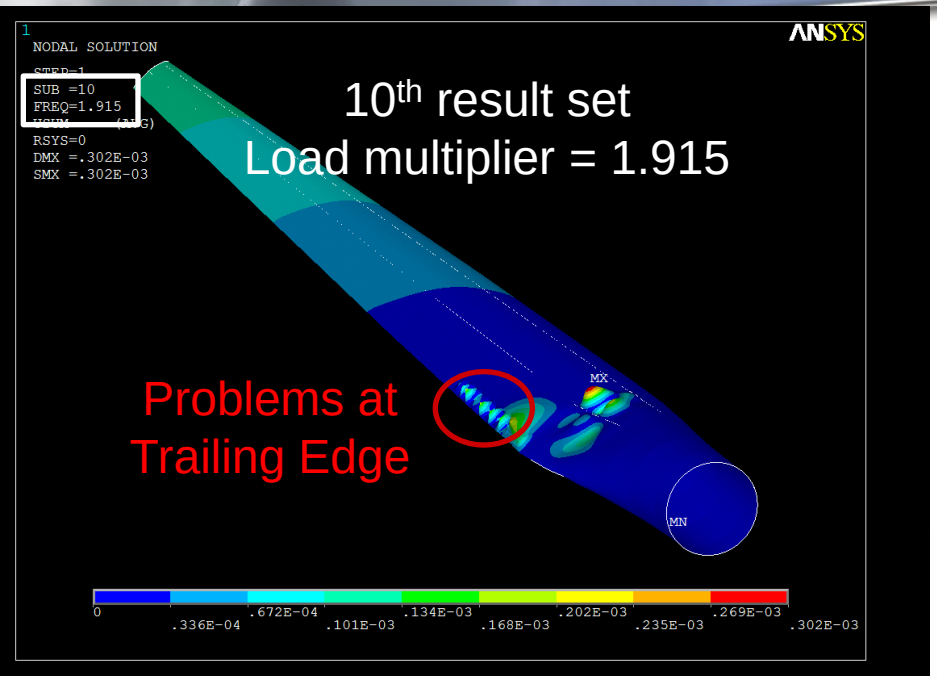


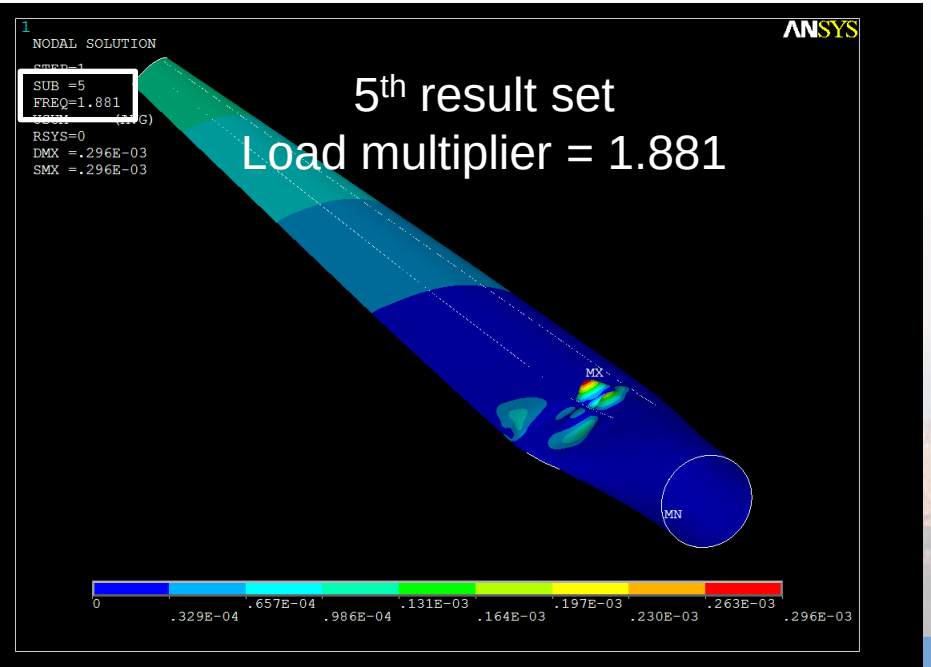


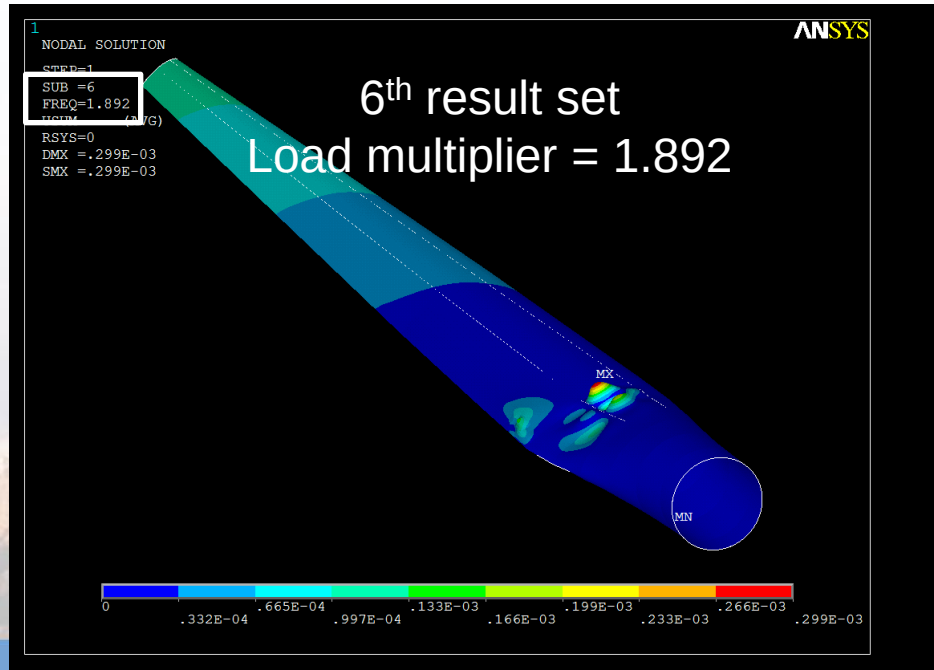


Eigen Buckling Analysis

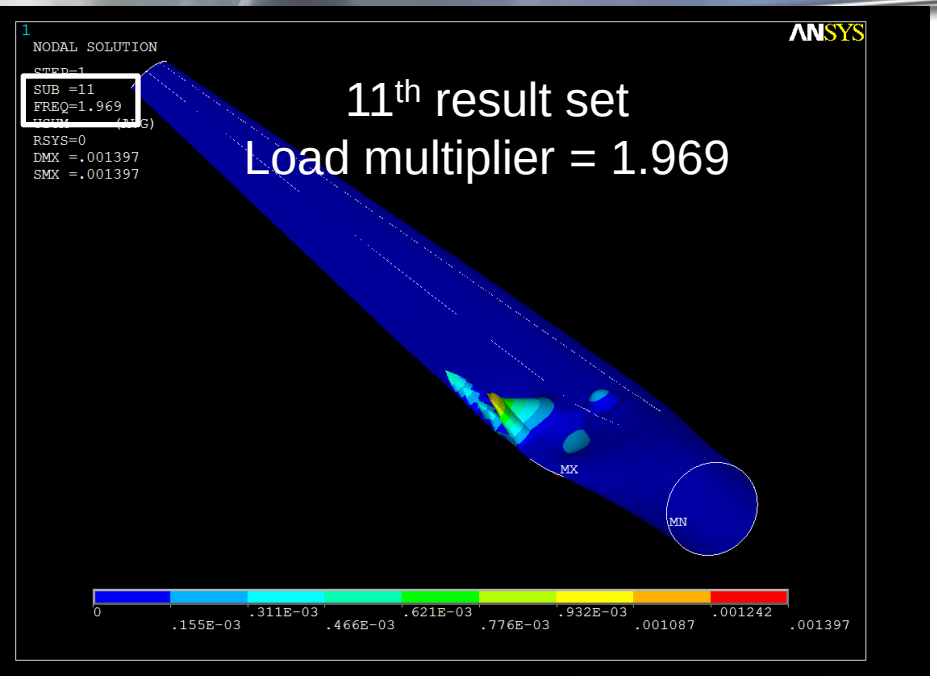
- **The Distributed-Load model appears to be less sensitive to Geometry/Meshing Quirks**

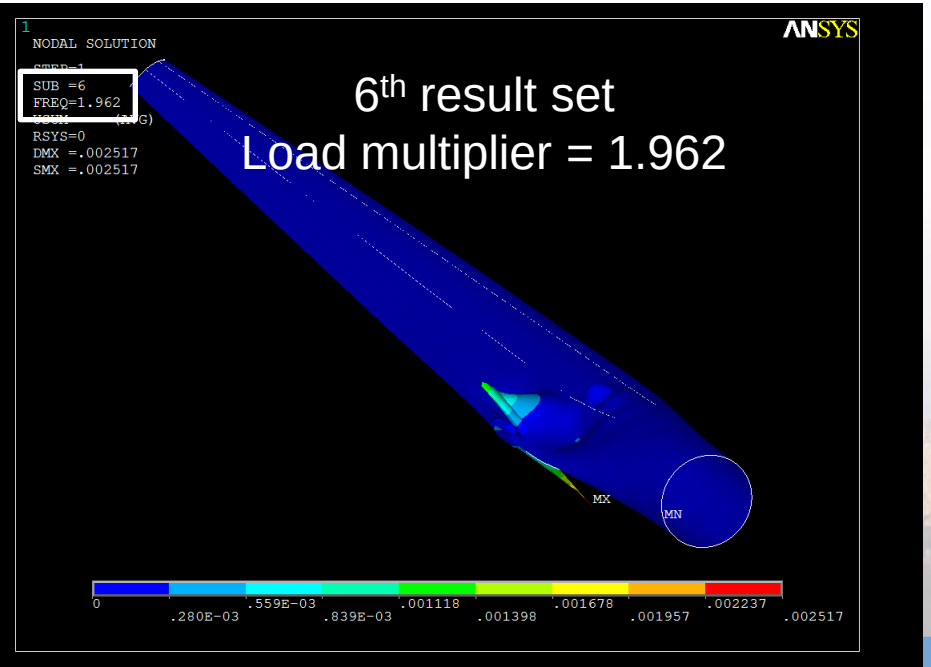


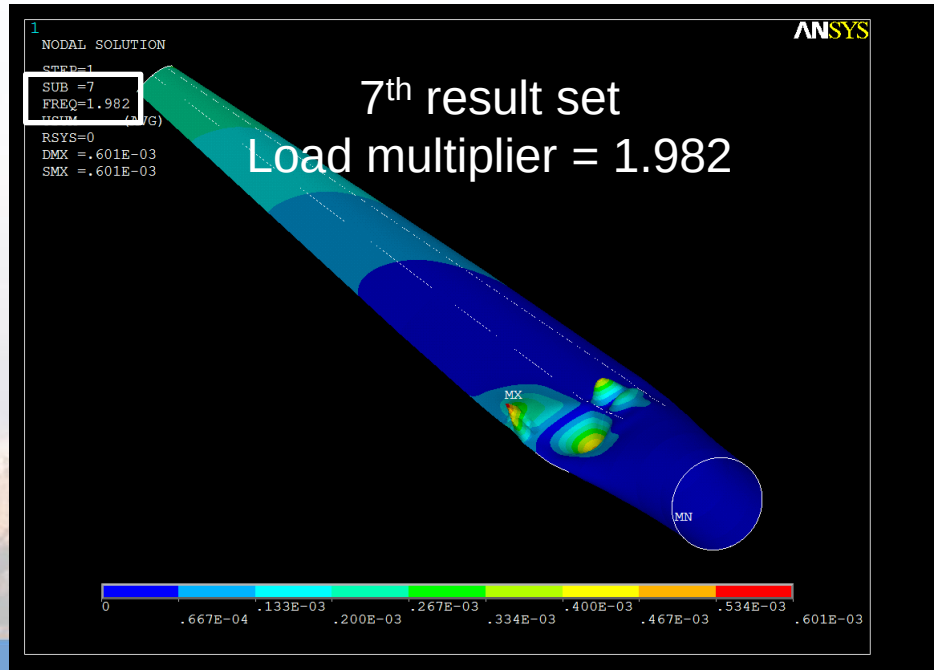




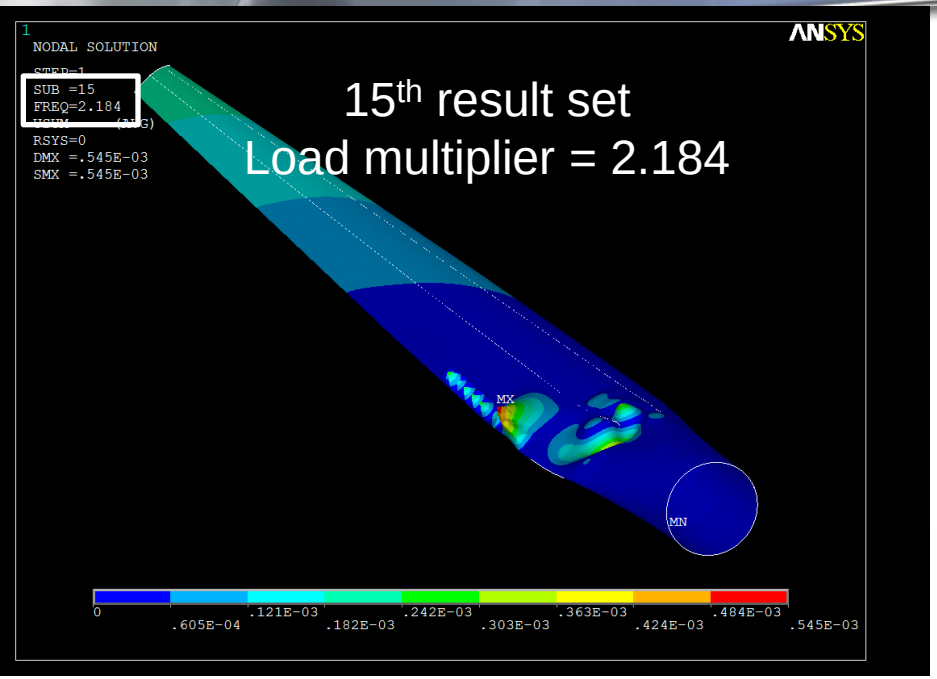
Eigen Buckling Analysis

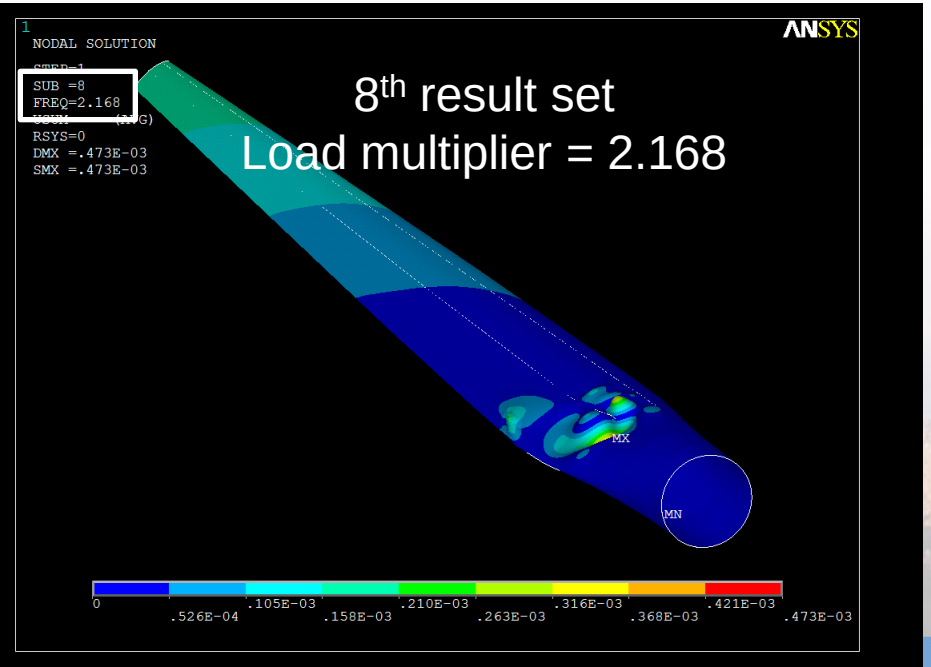


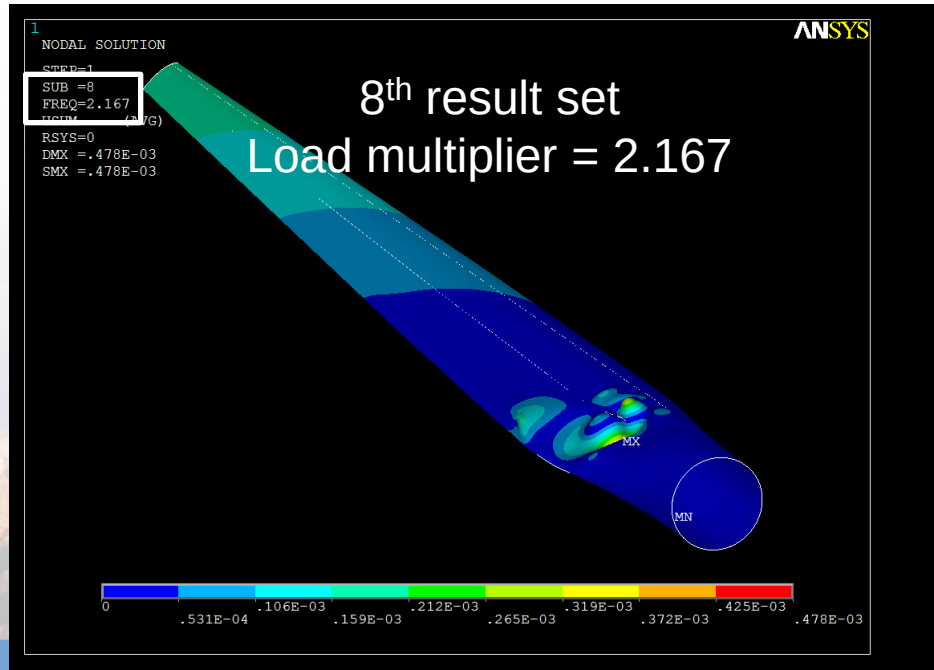




Eigen Buckling Analysis

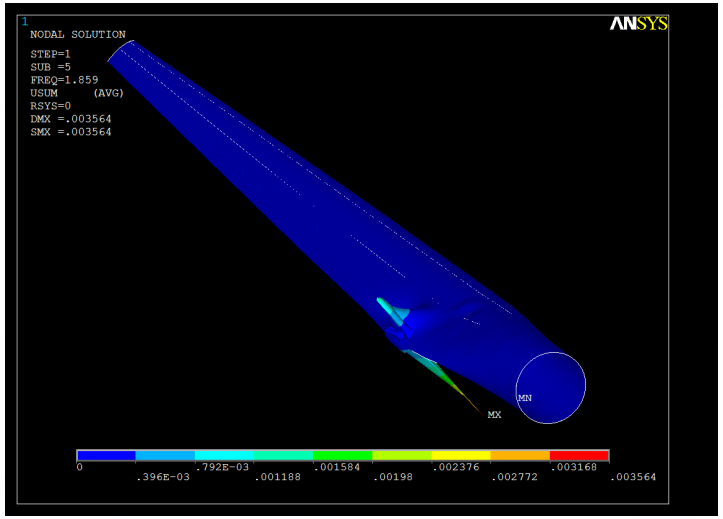


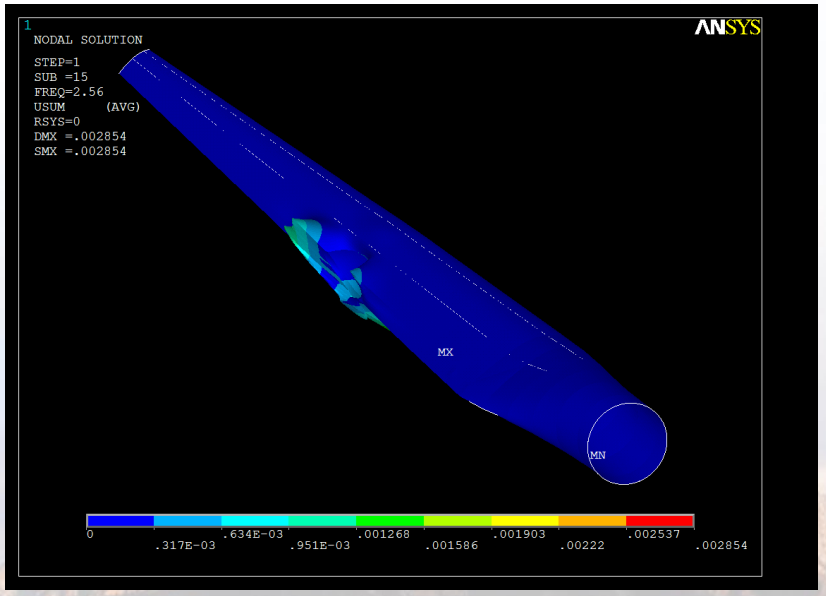


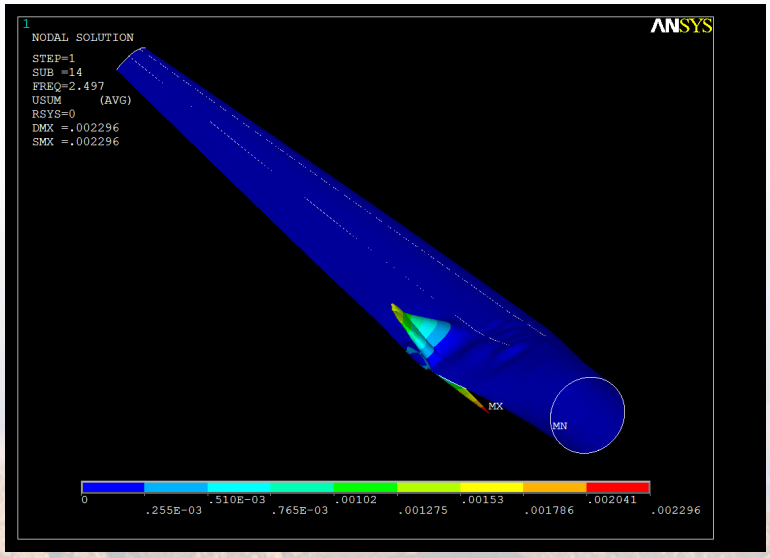


Eigen Buckling Analysis

- **However, Distributed-Load model does still display oddities at times**
- **Need to clean up geometry**







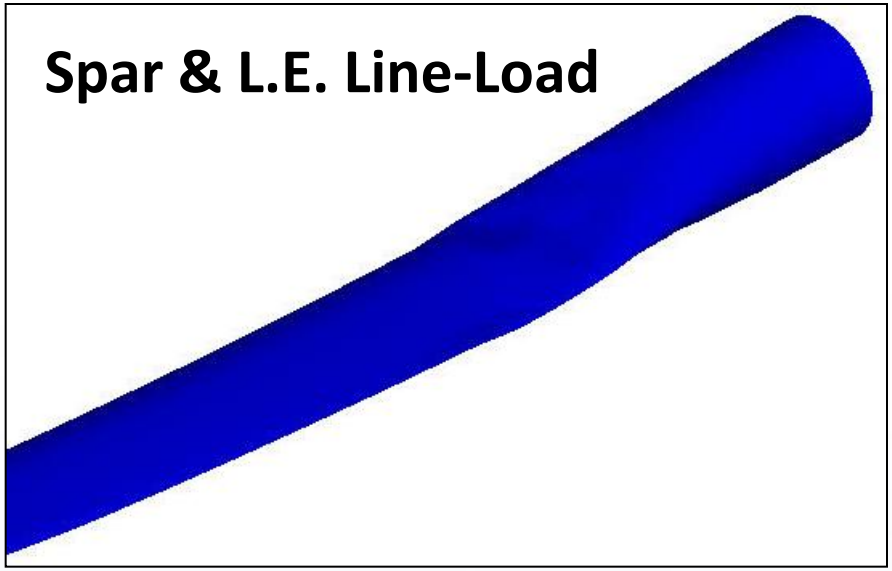
Summary of Results

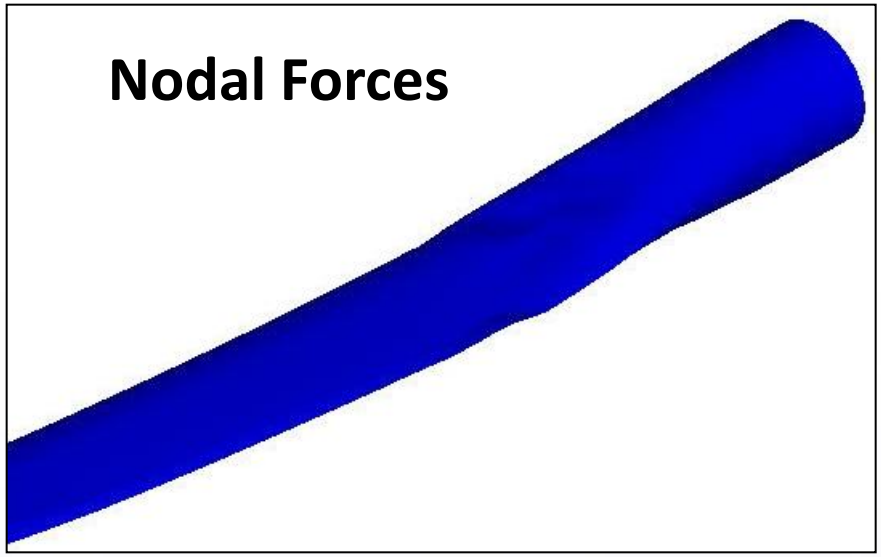
SET	Spar Force Line LOAD MULTIPLIER	Spar and L.E. Force Lines LOAD MULTIPLIER	Nodal Forces LOAD MULTIPLIER
1	0.75634	1.0741	1.0145
2	0.96211	1.4036	1.3384
3	1.2193	1.7167 (1st)	1.6605
4	1.4811	1.7583	1.7104 (1st)
5	1.6202	1.8807 (2nd)	1.8594
6	1.6908 (1st)	1.9619 (3rd?)	1.8916 (2nd)
7	1.7315	1.9888	1.9824 (3rd)
8	1.8183	2.1684 (4th)	2.1667 (4th)
9	1.9033	2.2161 (5th)	2.2166 (5th)
10	1.9147 (2nd)	2.2662 (6th)	2.2665 (6th)
11	1.9695 (3rd?)	2.3698 (7th)	2.3697 (7th)
12	1.9994	2.4448 (8th)	2.4397 (8th)
13	2.0468	2.4676 (9th)	2.4673 (9th)
14	2.1256	2.5834 (10th)	2.4970
15	2.1838 (4th)	2.6168	2.5605
16	2.2086	2.6643	2.5855 (10th)
17	2.2251 (5th)	2.6937	2.6023
18	2.2732 (6th?)	2.8206 (12th)	2.6297
19	2.3016	2.8516	2.6800 (11th)
20	2.3727	2.9312	2.8215 (12th)

Non-linear Buckling

- **Linear buckling analyses can be non-conservative**
- **Buckling with non-linear displacement was analyzed**
  - Used four-node SHELL181 elements (solution would not converge with SHELL281 elements)
  - Introduced displacement defect to initiate buckling
    - Shape taken from linear buckling analysis
    - Amplitudes of 10, 20, and 50 mm

Non-linear Buckling Results





Imperfection Size	Spar and L.E. Force Lines LOAD MULTIPLIER	Nodal Forces LOAD MULTIPLIER
10 mm	2.08	2.28
20 mm	2.00	2.19
50 mm	1.93	2.17

Conclusions

- We demonstrated a technique for mapping 1-D beam loads to FE model
- This blade model exhibited fewer spurious modes when loaded in both flap and edge
- Overall, results for this blade were relatively insensitive to load application method. Distributed loading may be important for non-linear buckling analysis.
- We will use this sort of analysis to improve our WindPACT 1.5MW model and support large blade designs.

Thank You