Efficient High-fidelity Modeling of Composite Wind Turbine Blades

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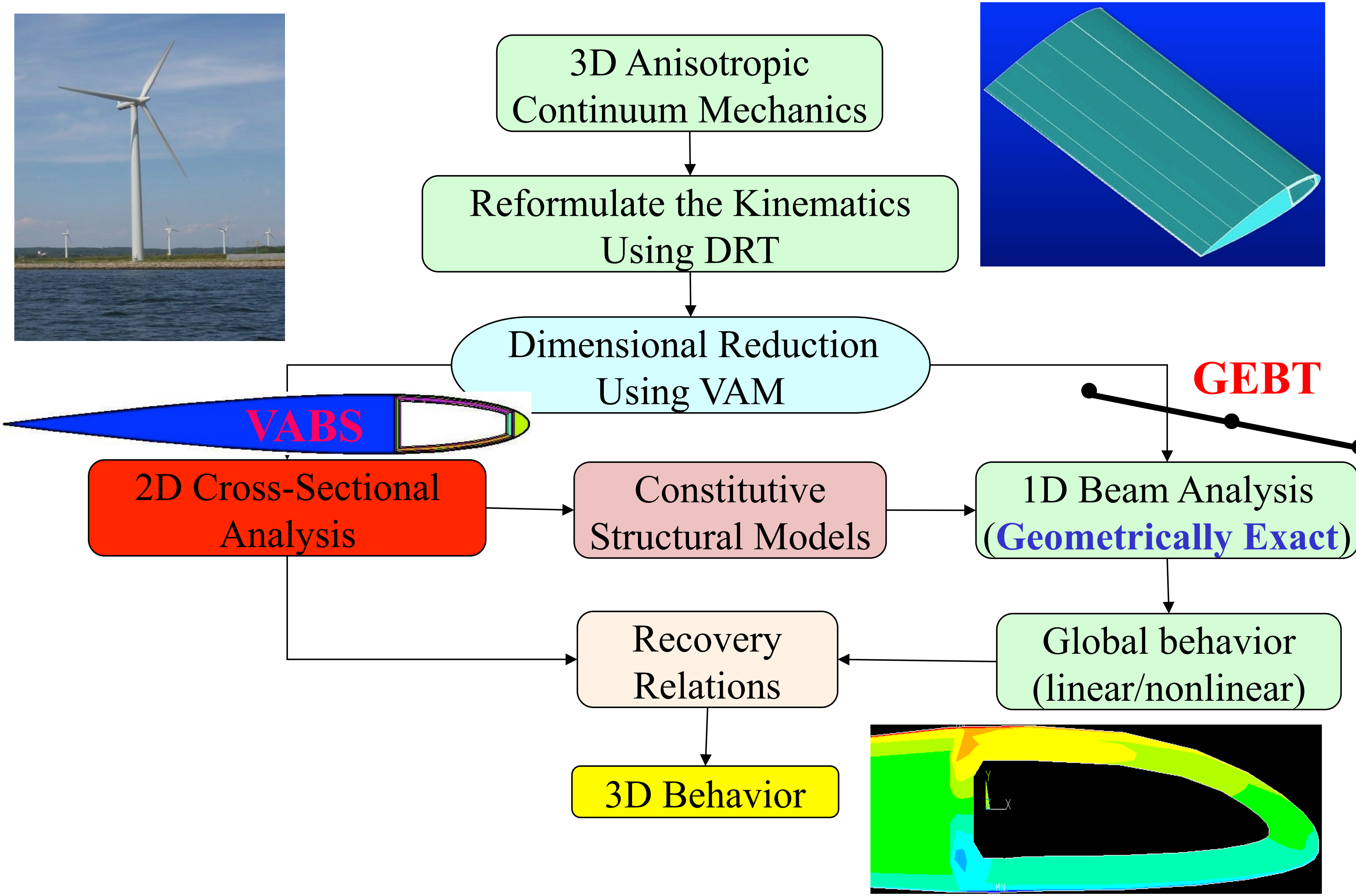
Goal, Objective, and Result

- **Goal: enable efficient high-fidelity beam models for computational design**

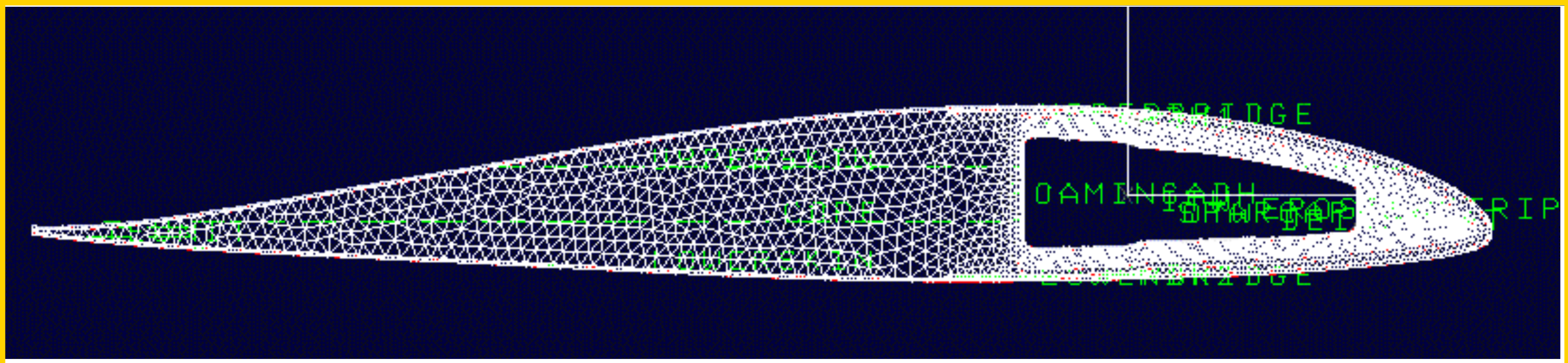
- Objective: beam analysis tools that can
  - Capture geometrical nonlinearity systematically.
  - Capture anisotropic and heterogeneous behavior of composite materials rigorously.
  - Achieve the speed of computational design without significant loss of accuracy comparing to the ultimate accuracy obtained by 3D nonlinear FEA.

- Result: GEBT + VABS

Efficient High-fidelity Beam Modeling



VABS: Cross-sectional Tool

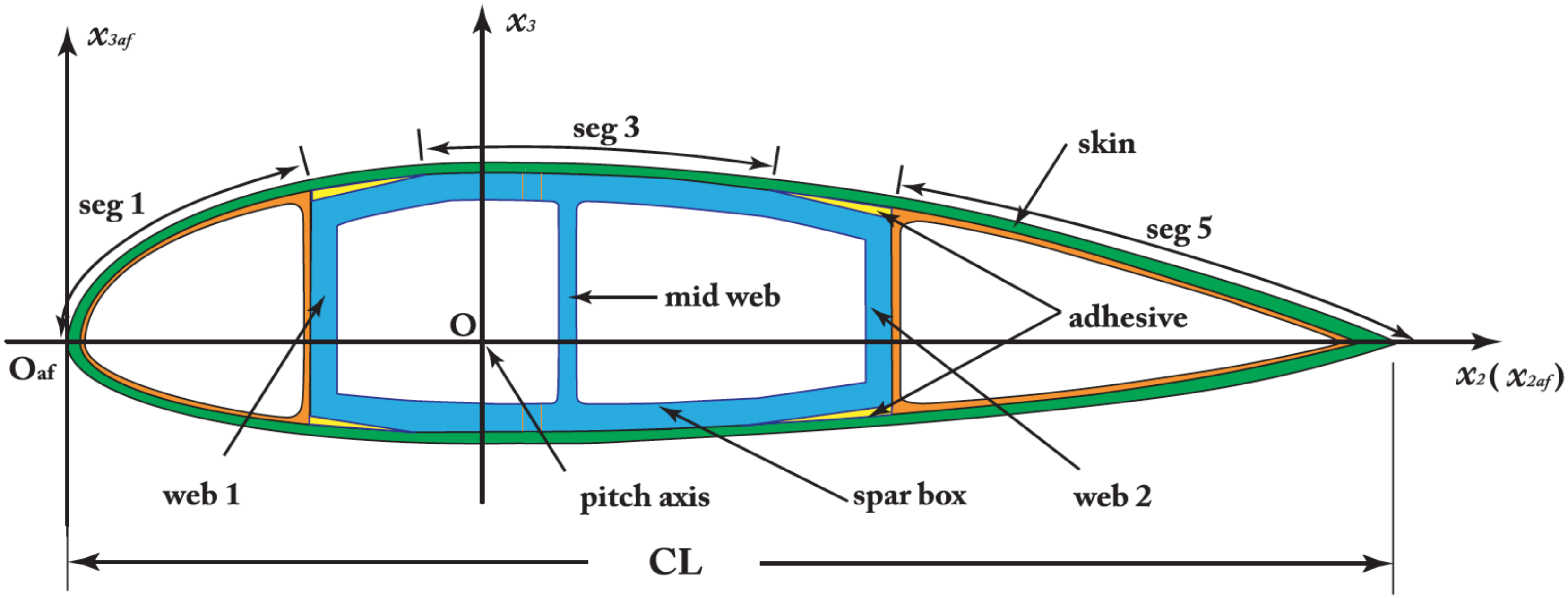


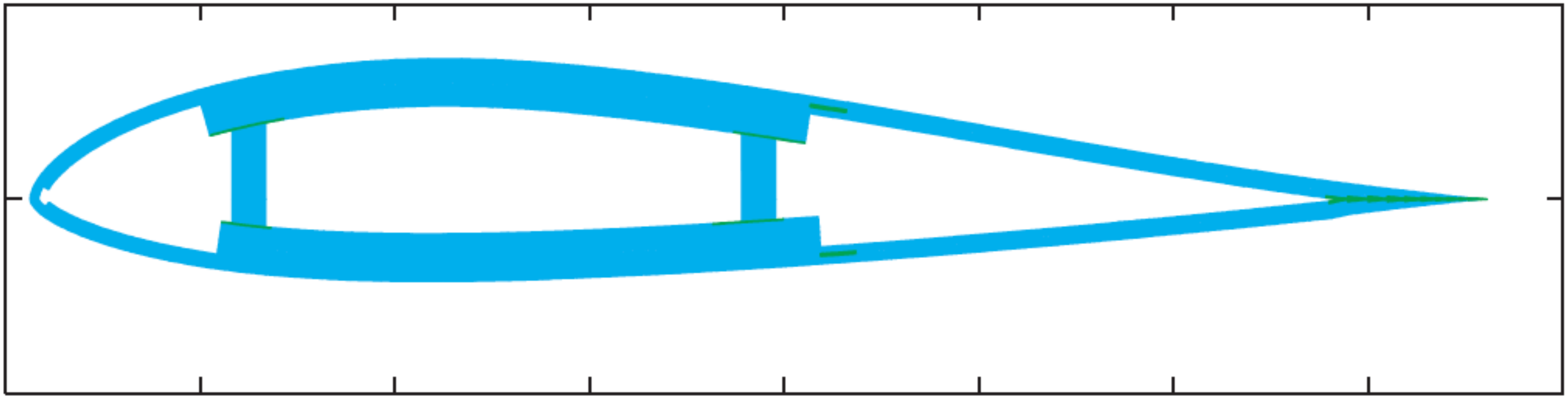
- VABS takes a finite element discretization of the sectional geometry and material as inputs to calculate sectional properties, which are needed for beam analysis code to predict the global behavior. VABS can also recover 3D displacements/strains/stresses over the section: a link between 3D and 1D

- VABS can be used independently for structural design of wing sections (topology and material): e.g., maximize the torsional stiffness while maintain the desired mass or minimize the difference between the aerodynamic center and elastic axis

- VABS provides high-fidelity information of composites with no additional computing cost to the 1D beam analysis

VABS Example: MH 104 Airfoil



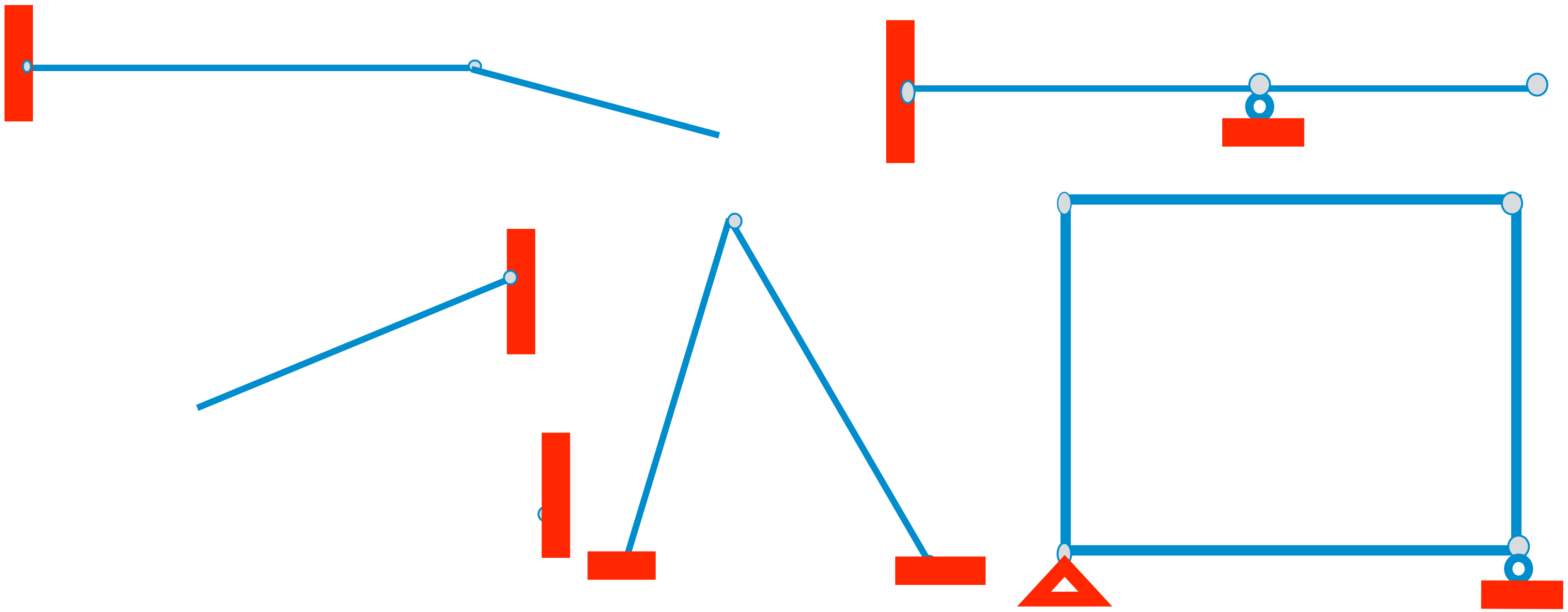


VABS Example: Results

Table IX. Sectional properties of the wind turbine blade section at station 2.

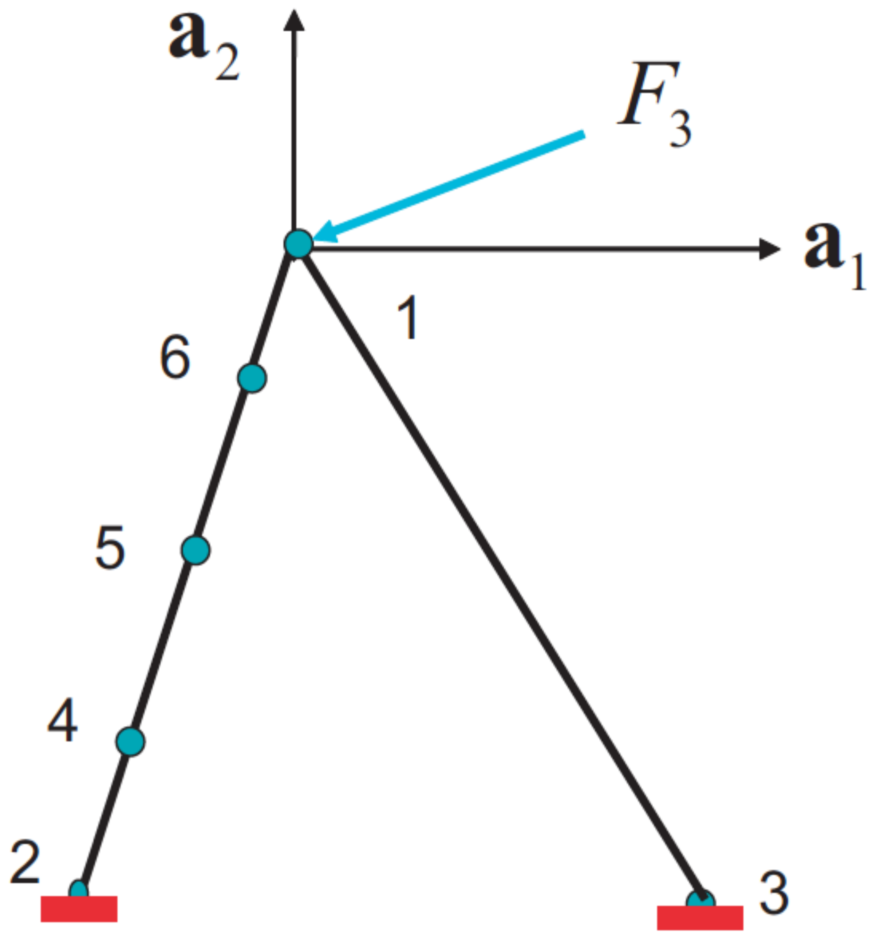
Variables	PreComp	CROSTAB	VABS	% Diff. (PreComp)	% Diff. (CROSTAB)
EI_{22}	6.363E+04	8.608E+05	5.878E+04	8.253	1.364E+03
EI_{33}	2.784E+06	2.481E+06	1.586E+06	75.570	56.487
GJ	4.103E+04	9.379E+04	7.027E+04	41.613	33.473
EA	2.090E+08	2.115E+08	1.533E+08	36.375	38.026
S_{34}	–2.149E+04	2.433E+05	4.159E+04	151.669	485.000
S_{13}	–1.558E+04	1.187E+07	–4.297E+05	96.374	2.861E+03
S_{14}	–7.272E+06	1.332E+06	–7.224E+06	0.662	118.444
S_{23}	–9.178E+02	1.671E+07	1.214E+02	856.218	1.376E+07
S_{24}	1.833E+04	–4.429E+06	6.274E+03	192.172	7.070E+04
S_{12}	4.719E+03	–3.037E+07	–1.314E+04	135.911	2.310E+05
μ	20.050	22.07	16.763	19.609	31.679
i_{22}	7.229E–03	0.0208	7.017E–03	3.025	196.177
i_{33}	0.2644	0.318	0.174	52.144	82.918
x_{m2}	0.089	0.0871	0.0619	43.672	40.624
x_{m3}	0.006	–0.0040	0.0065	7.523	161.436
x_{t2}	0.092	–0.0051	0.0492	86.860	110.359
x_{t3}	0.007	0.0659	0.0069	1.722	857.642
x_{s2}	0.058	/	0.0012	4.719E+03	/
x_{s3}	0.007	/	0.0098	28.210	/
θ	–0.8490	4.210	–1.117	24.023	476.620

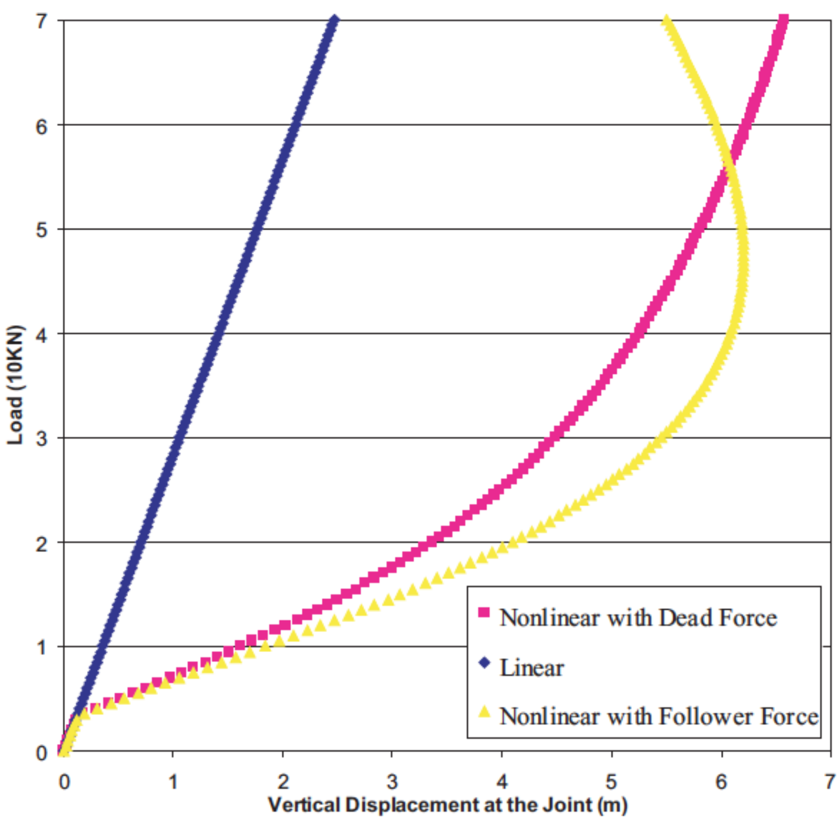
Geometrically Exact Beam Theory (GEBT)



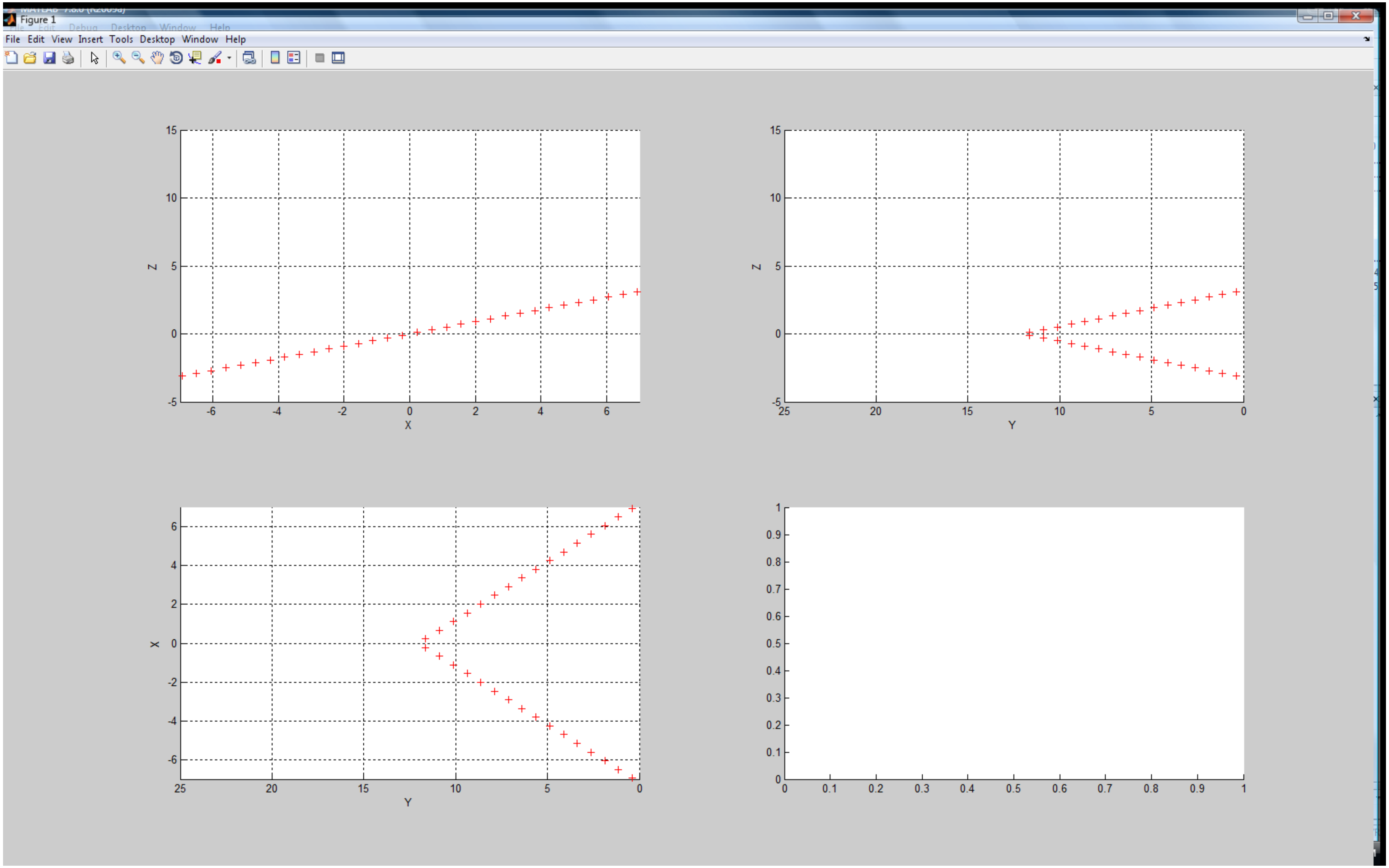
- GEBT carries out a 1D analysis of structures which can be modeled as an assembly of beams
- GEBT uses sectional properties from VABS and provides information for VABS to recover 3D stress state
- GEBT obtains the complete set of beam variables including displacements, rotations, forces, and moments

GEBT Example: Beam Assembly

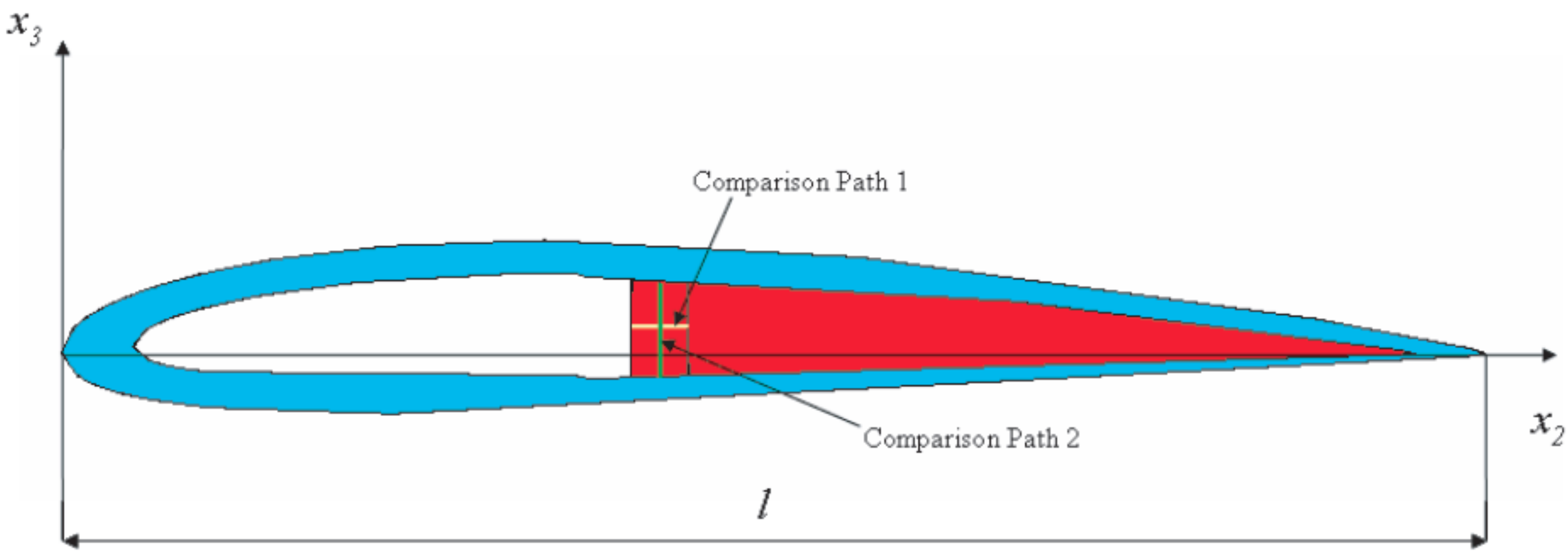




GEBT Example: Dead Force

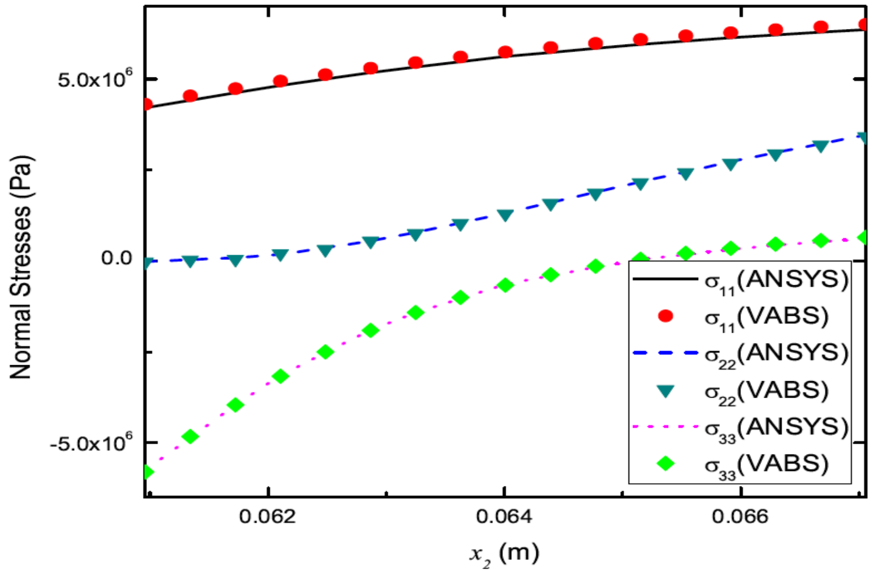


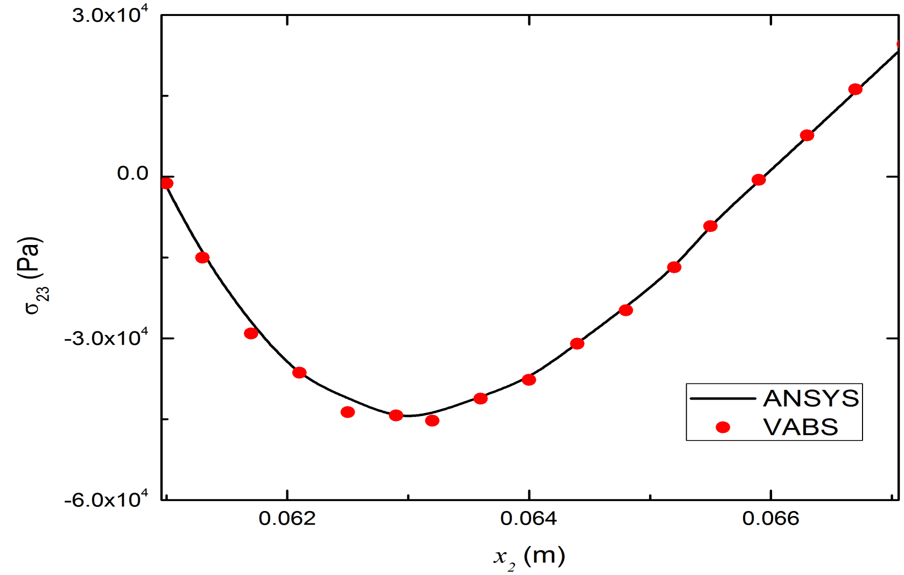
Stress Recovery

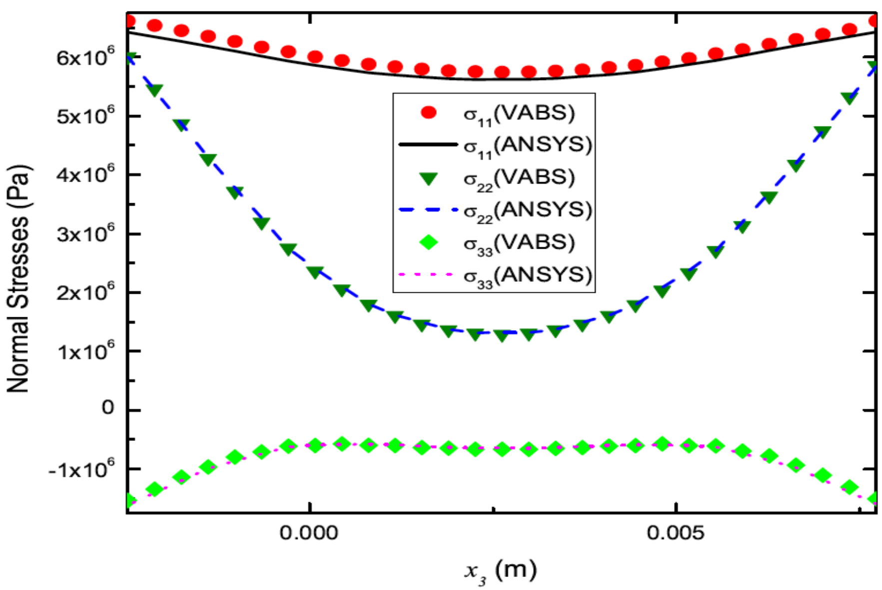


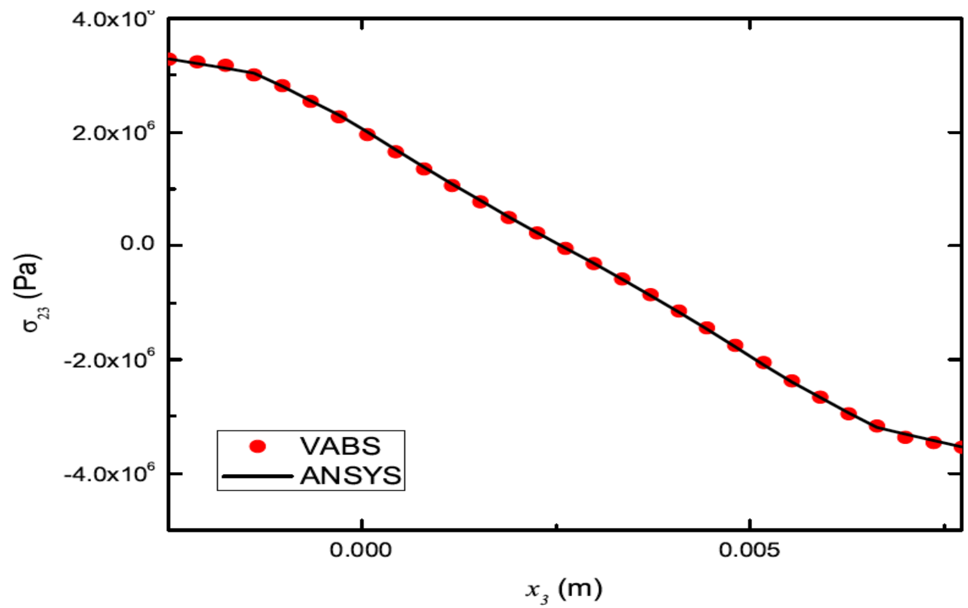
- NACA2412 Airfoil
- Skin: Aluminum
- Core: Aerospace Foam
- Uniform Temperature Change: 100°C
- Comparison Path 1: Chord-Length Direction
- Comparison Path 2: Through-the-Thickness Direction

Stress Recovery: Accuracy



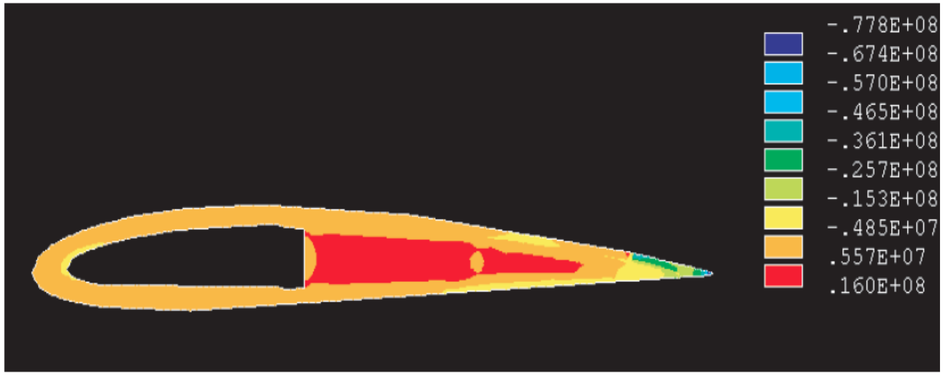




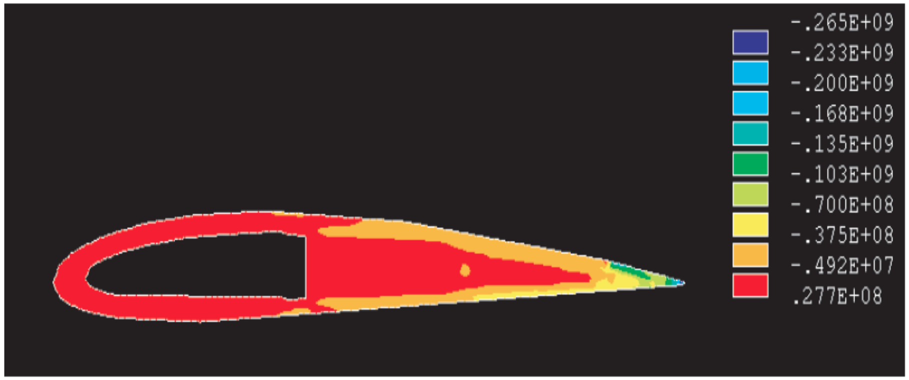


Stress Recovery: Contour Plot

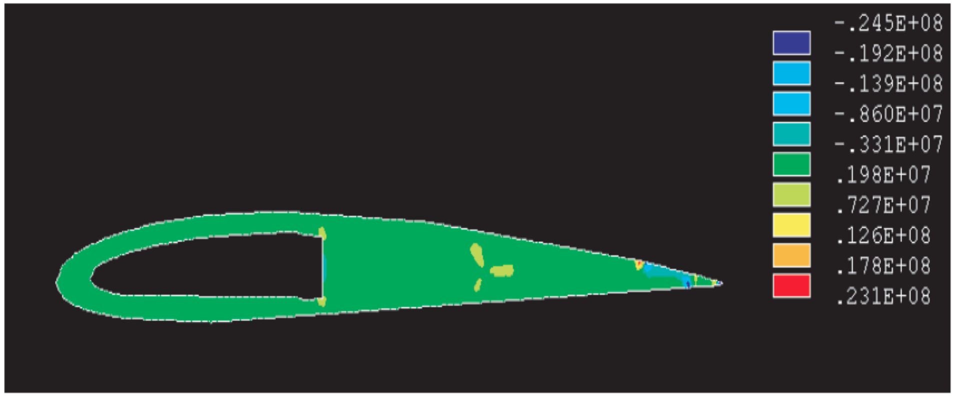
σ_{11}



σ_{22}



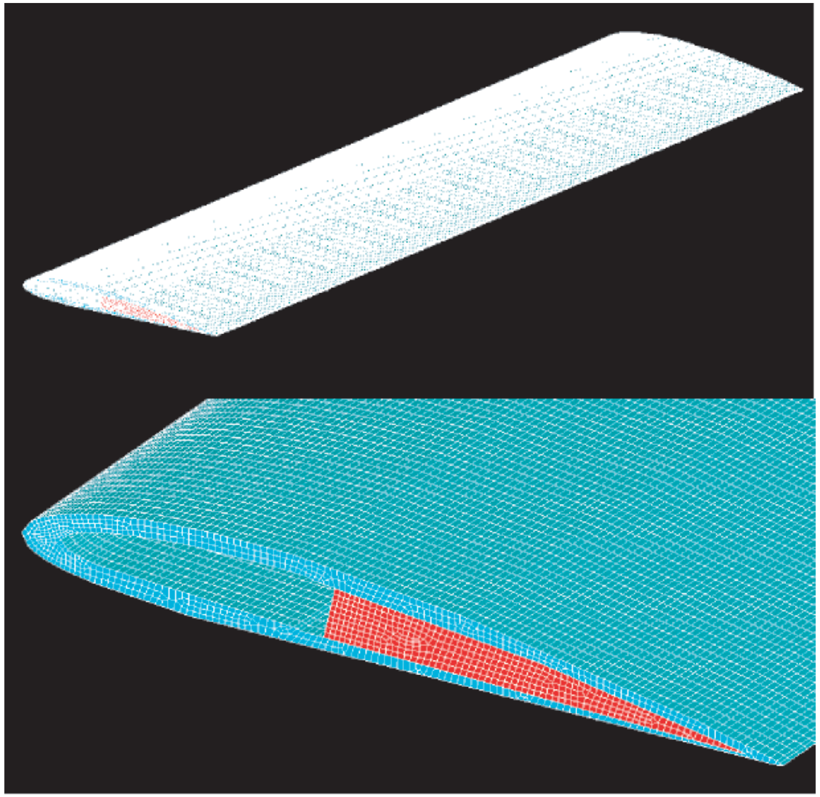
σ_{33}



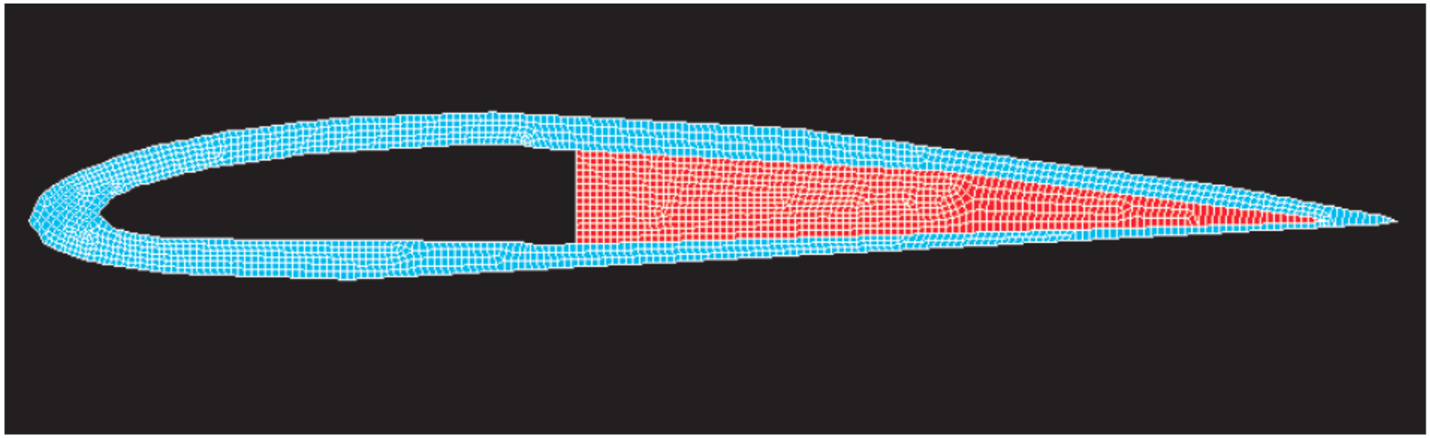
σ_{23}

Stress Recovery: Efficiency

3D Model: ANSYS



2D Model: VABS

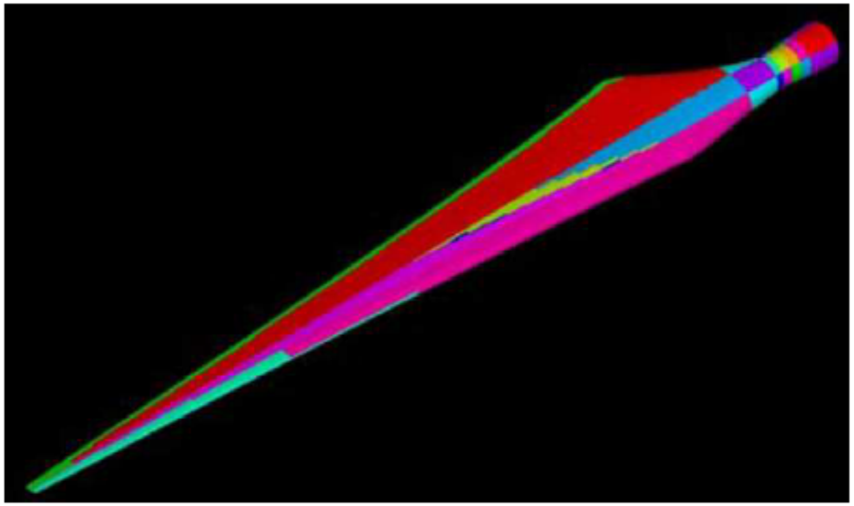


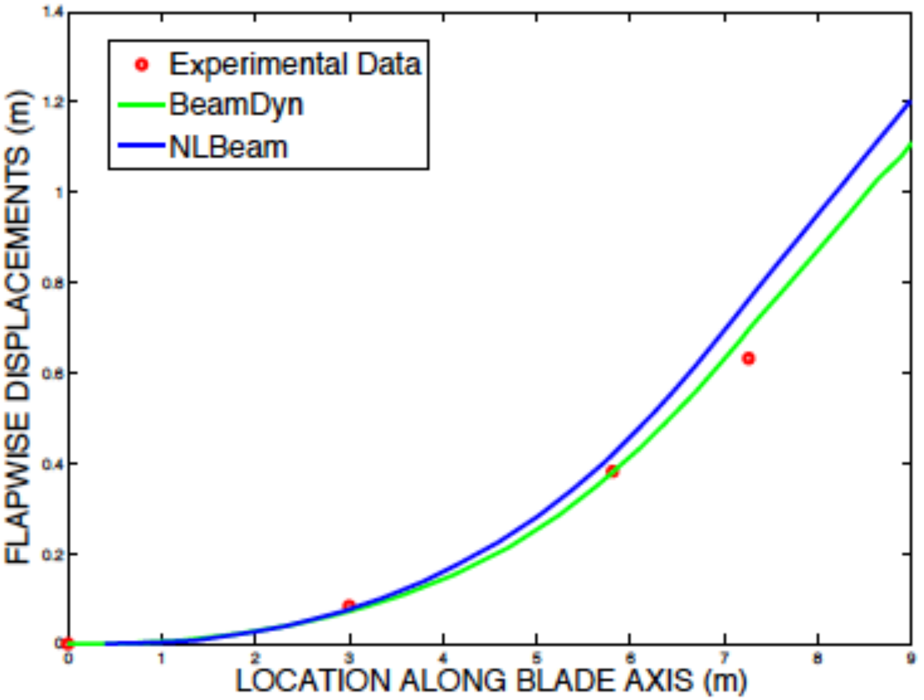
Stress Recovery: Efficiency

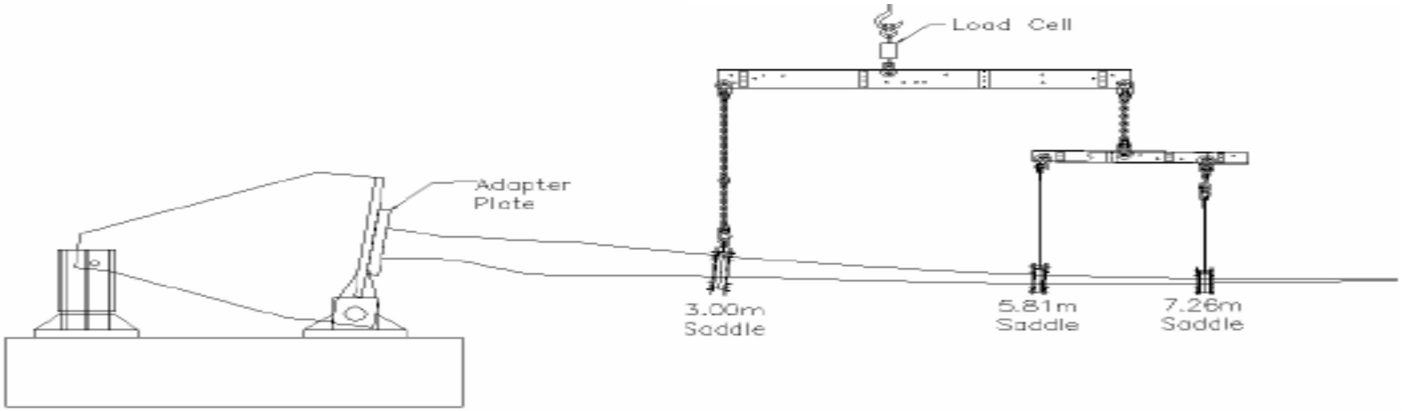
	ANSYS 3D	VABS
Element Type	SOLID186	8-noded quadrilateral
Number of Elements	362,408	2,459
Number of Nodes	1,638,866	7,965
Running Time	3h 5min 23s	11s + 26s

- Computing Server
  - AMD Opteron™ Processor 6174 2.20 GHz (2 Processor)
  - 128 GB RAM

Wind Turbine Blades: CX-100

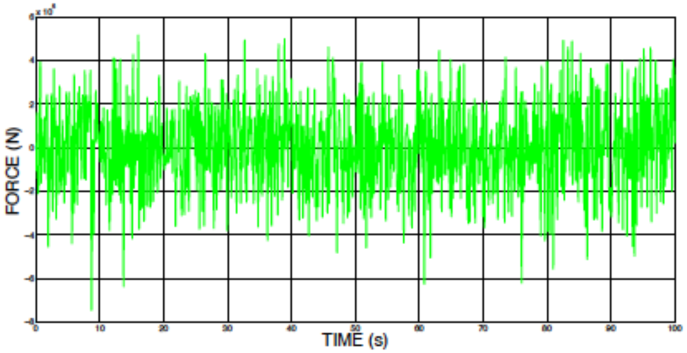




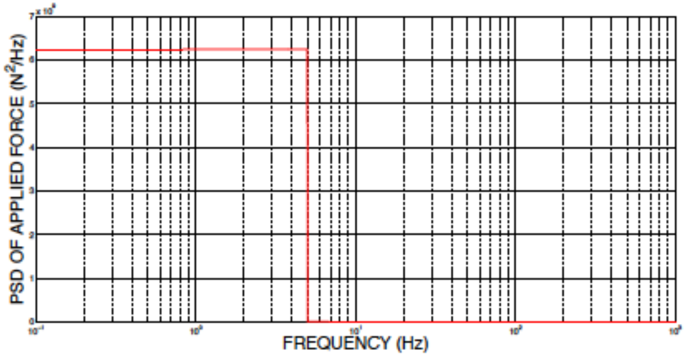


Wind Turbine Blade: NREL 5MW

- NREL 5-MW Blade; Cantilevered at root
- White noise force applied at the free tip along flap direction
- Time History of Applied Force

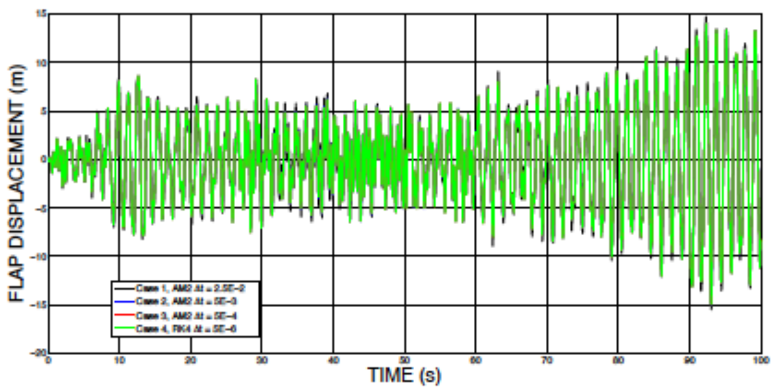


- PSD of Applied Force

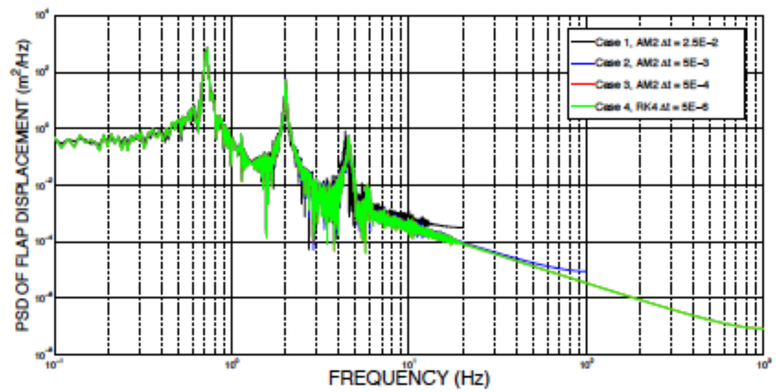


Wind Turbine Blade: NREL 5MW

- Flapwise Response



- PSD of Flapwise Response



- The spikes at 0.7 Hz and 2 Hz correspond to the first and second blade flapwise natural frequencies
- The spike above 5 Hz – above the frequency range of excitation – is brought about by nonlinear and coupling effects

Conclusions & Future Work

- Efficient high-fidelity beam models can avoid expensive cost associated with 3D FEA
  - VABS for cross-sectional analysis and 3D fields recovery
  - GEBT for 1D beam analysis for global behavior including linear, nonlinear, static, or dynamic (time marching or eigenvalue analysis)
- Future Work
  - Multi-scale design and analysis of composite wind turbine blades
  - Multi-physics design and analysis of smart wind turbine blade
  - Extend application to distributed wind and water/wave energy turbines