VABS™

POWERING SIMPLE BEAM ELEMENTS WITH DETAILED 3D FEA FIDELITY

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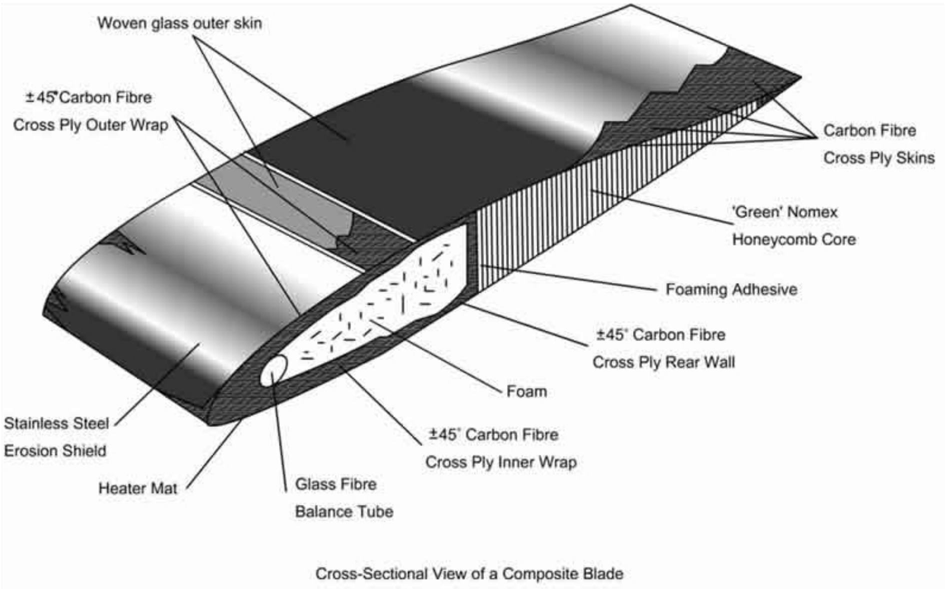
The Problem



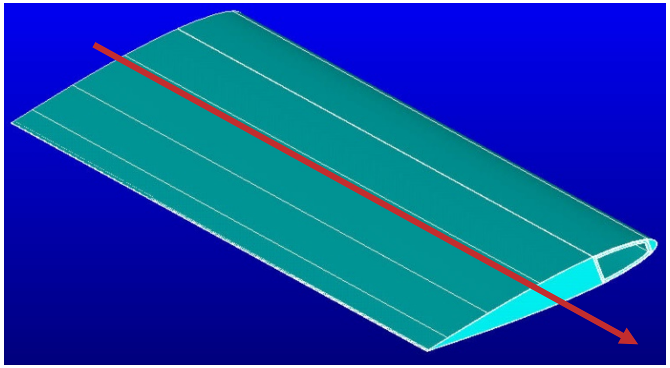
Cross-Sectional View of a Composite Blade

3D FEA

At least one solid elements/layer
10^9 DOFs/blade
Not suitable for design & optimization
Smeared property approach improves efficiency but loses significant accuracy

Length: 8.6 m
Chord: 0.72 m.
D-spar: 60 graphite/epoxy plies
Ply thickness: 125 microns

VABS: Beam Constitutive Modeling



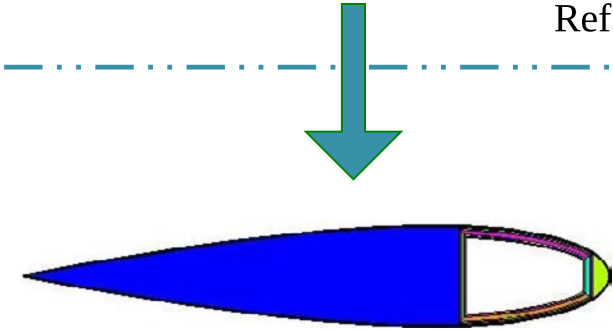
Reference line

3D Elasticity

$$\sigma_{ij,j} + f_i = 0$$

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$$

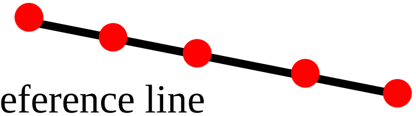
$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{12} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{13} & c_{23} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{14} & c_{24} & c_{34} & c_{44} & c_{45} & c_{46} \\ c_{15} & c_{25} & c_{35} & c_{45} & c_{55} & c_{56} \\ c_{16} & c_{26} & c_{36} & c_{46} & c_{56} & c_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{Bmatrix}$$



VABS™

$$\begin{Bmatrix} F_1 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{23} & S_{24} \\ S_{13} & S_{23} & S_{33} & S_{34} \\ S_{14} & S_{24} & S_{34} & S_{44} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix}$$

+



Reference line

1D beam analysis

$$\begin{aligned} \gamma_{11} &= \bar{u}_1' \\ \kappa_1 &= \Phi_1' \\ \kappa_2 &= -\bar{u}_3'' \\ \kappa_3 &= \bar{u}_2'' \end{aligned}$$

$$\begin{aligned} \frac{\mathrm{d}F_1}{\mathrm{d}x_1} + p_1 &= 0 \\ \frac{\mathrm{d}M_1}{\mathrm{d}x_1} + q_1 &= 0 \\ \frac{d^2 M_2}{\mathrm{d}x_1^2} + p_3 + \frac{\mathrm{d}q_2}{\mathrm{d}x_1} &= 0 \\ \frac{d^2 M_3}{\mathrm{d}x_1^2} - p_2 + \frac{\mathrm{d}q_3}{\mathrm{d}x_1} &= 0 \end{aligned}$$

Introduction to VABS Theory

- Minimize kinetic energy loss.
- A diagonal mass matrix is possible if blade axis is at the mass center and sectional coordinates are the principal inertia axes.

$$\mathcal{K} = \frac{1}{2} \begin{Bmatrix} V_1 \\ V_2 \\ V_3 \\ \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{Bmatrix}^T \begin{bmatrix} \mu & 0 & 0 & 0 & \mu x_{m3} & -\mu x_{m2} \\ & \mu & 0 & -\mu x_{m3} & 0 & 0 \\ & & \mu & \mu x_{m2} & 0 & 0 \\ & & & i_{22}+i_{33} & 0 & 0 \\ & & symmetric & & i_{22} & -i_{23} \\ & & & & & i_{33} \end{bmatrix} \begin{Bmatrix} V_1 \\ V_2 \\ V_3 \\ \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{Bmatrix}$$

Introduction to VABS Theory

- Euler-Bernoulli model

$$\begin{Bmatrix} F_1 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{23} & S_{24} \\ S_{13} & S_{23} & S_{33} & S_{34} \\ S_{14} & S_{24} & S_{34} & S_{44} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix}$$

- Timoshenko model

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45} & S_{46} \\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55} & S_{56} \\ S_{16} & S_{26} & S_{36} & S_{46} & S_{56} & S_{66} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ 2\gamma_{12} \\ 2\gamma_{13} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix}$$

- 1D beam analysis should be changed to allow fully populated stiffness matrices.

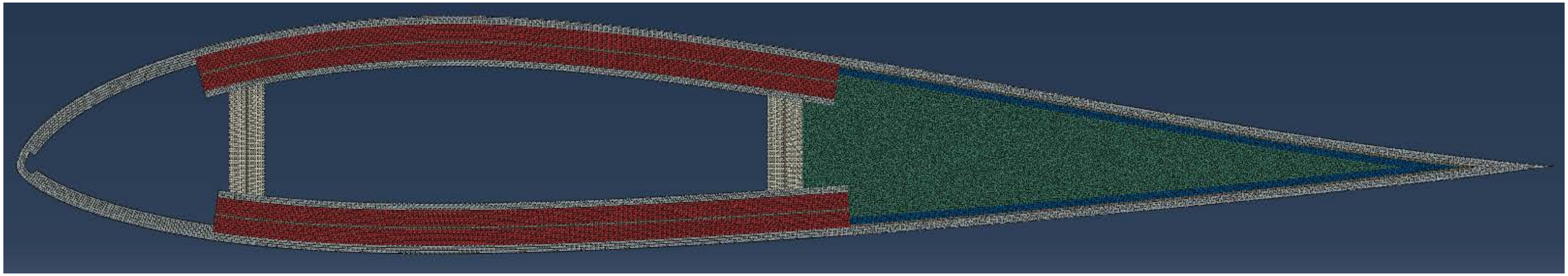
Introduction to VABS Theory

- Vlasov model: important for thin-walled beams with open sections

$$\begin{Bmatrix} F_1 \\ M_1 \\ M_2 \\ M_3 \\ M_\omega \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} \\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25} \\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35} \\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45} \\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \\ \kappa_1' \end{Bmatrix}$$

- VABS can also
  - Deal with trapeze effect, oblique sections
  - Locate neutral axis, principal bending/inertia axes, shear center
  - Recover 3D displacement/strain/stress
  - Model beams made of smart materials (coupled thermo-elasto-electro-magnetic behavior)

What Can VABS Do for You?



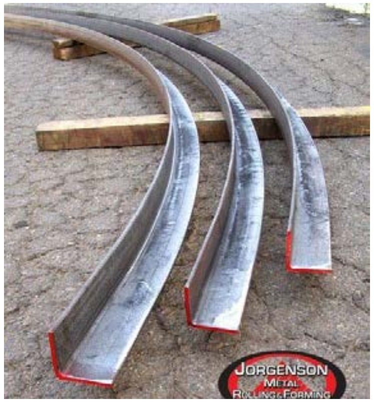
- **VABS** takes a finite element discretization of sectional geometry and material as input to calculate sectional properties, which are needed for any beam analysis code to predict global behavior. VABS also recovers 3D displacements/strains/stresses over the section.
- **VABS** can be used independently for **structural design of beam sections** (topology and material): e.g., maximize torsional stiffness while maintain desired center of gravity.
- **VABS** powers conventional beam elements with the fidelity of 3D detailed FEA for geometry representation and prediction with negligible additional computing time.

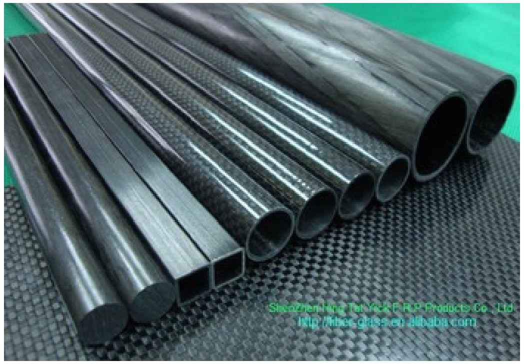
VABS: Efficient High-Fidelity Modeling of Composite Slender Structures

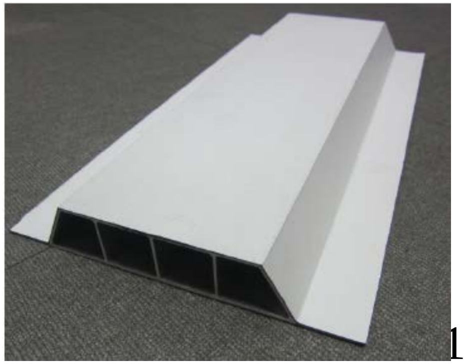
- A unique technology continuously funded by US Army since 1988 (28 yrs, 3 more to come).
- *VABS as a Tool for Real Blade Analysis, Design*, & Certification, Task 3 of Georgia Tech Vertical Lift Center of Excellence (2017-2019).
- Tool of choice for helicopter industry and wind turbine industry.
- Efficient high-fidelity solutions for slender parts: one dimension >> two other dimensions

Related Problems

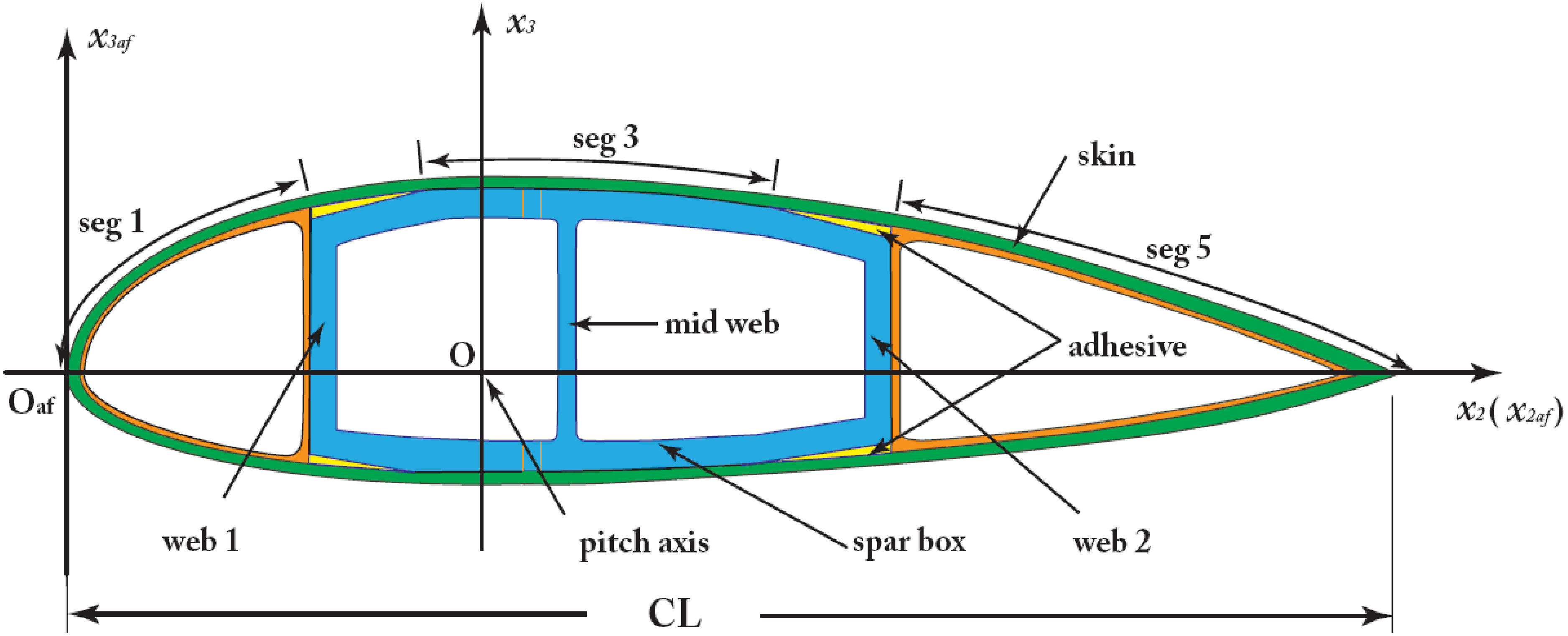
Related Problems





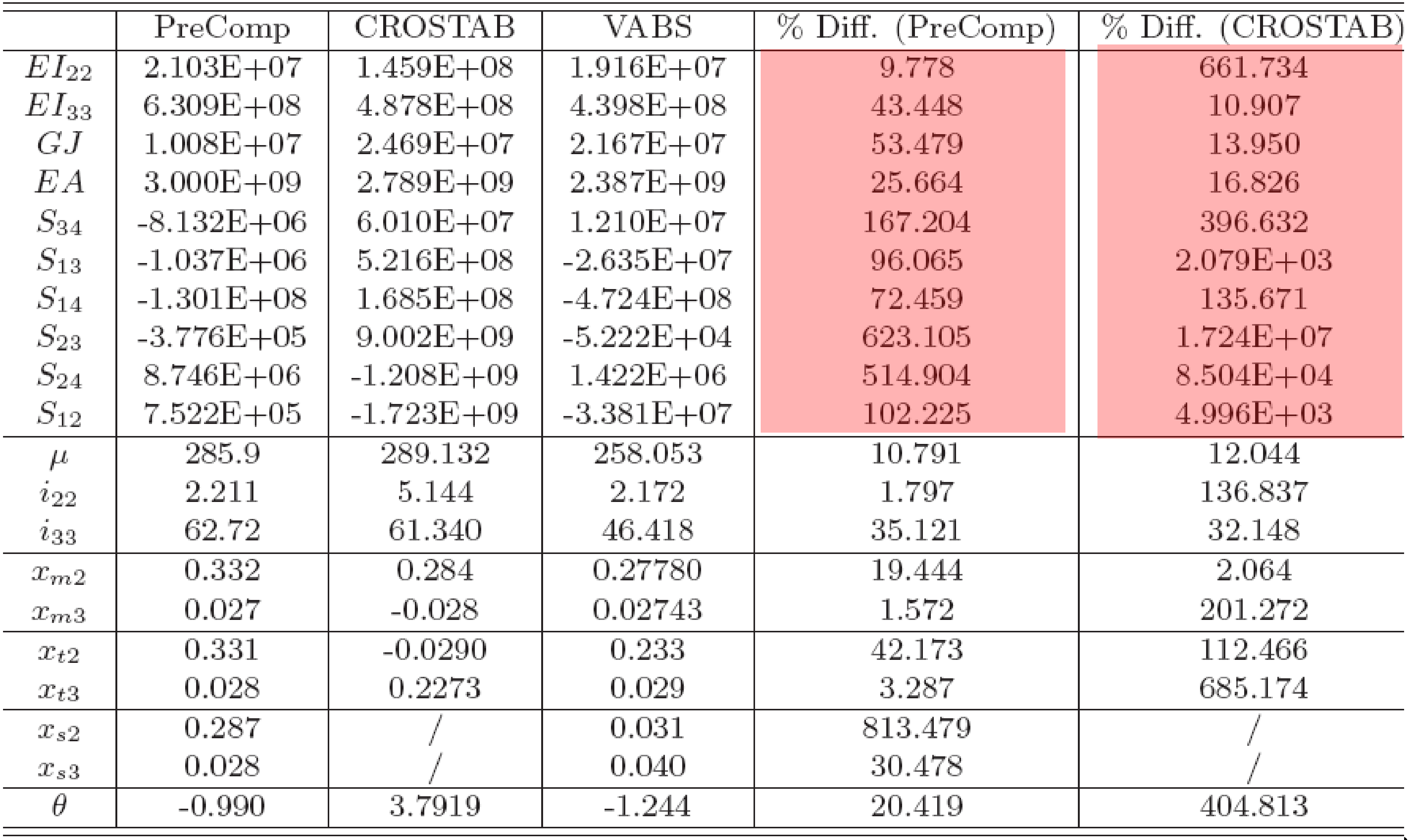


Properties of a Wind Turbine Blade



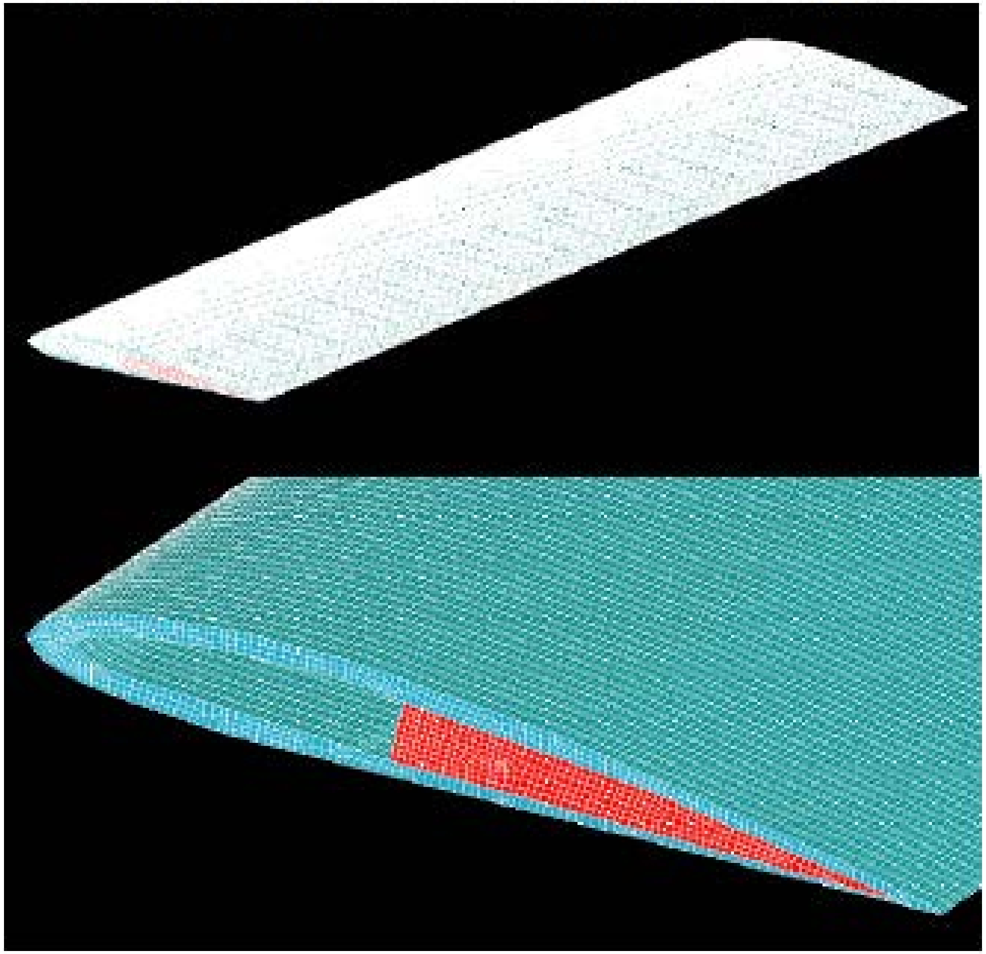
Chen, H. and Yu, W. and Capellaro, M.: “A Critical Assessment of Computer Tools for Calculating Composite Wind Turbine Blade Properties,” *Wind Energy*, vol. 13, no. 6, 2010, pp. 497-516.

Properties of a Wind Turbine Blade



	PreComp	CROSTAB	VABS	% Diff. (PreComp)	% Diff. (CROSTAB)
EI_{22}	2.103E+07	1.459E+08	1.916E+07	9.778	661.734
EI_{33}	6.309E+08	4.878E+08	4.398E+08	43.448	10.907
GJ	1.008E+07	2.469E+07	2.167E+07	53.479	13.950
EA	3.000E+09	2.789E+09	2.387E+09	25.664	16.826
S_{34}	-8.132E+06	6.010E+07	1.210E+07	167.204	396.632
S_{13}	-1.037E+06	5.216E+08	-2.635E+07	96.065	2.079E+03
S_{14}	-1.301E+08	1.685E+08	-4.724E+08	72.459	135.671
S_{23}	-3.776E+05	9.002E+09	-5.222E+04	623.105	1.724E+07
S_{24}	8.746E+06	-1.208E+09	1.422E+06	514.904	8.504E+04
S_{12}	7.522E+05	-1.723E+09	-3.381E+07	102.225	4.996E+03
μ	285.9	289.132	258.053	10.791	12.044
i_{22}	2.211	5.144	2.172	1.797	136.837
i_{33}	62.72	61.340	46.418	35.121	32.148
x_{m2}	0.332	0.284	0.27780	19.444	2.064
x_{m3}	0.027	-0.028	0.02743	1.572	201.272
x_{t2}	0.331	-0.0290	0.233	42.173	112.466
x_{t3}	0.028	0.2273	0.029	3.287	685.174
x_{s2}	0.287	/	0.031	813.479	/
x_{s3}	0.028	/	0.040	30.478	/
θ	-0.990	3.7919	-1.244	20.419	404.813

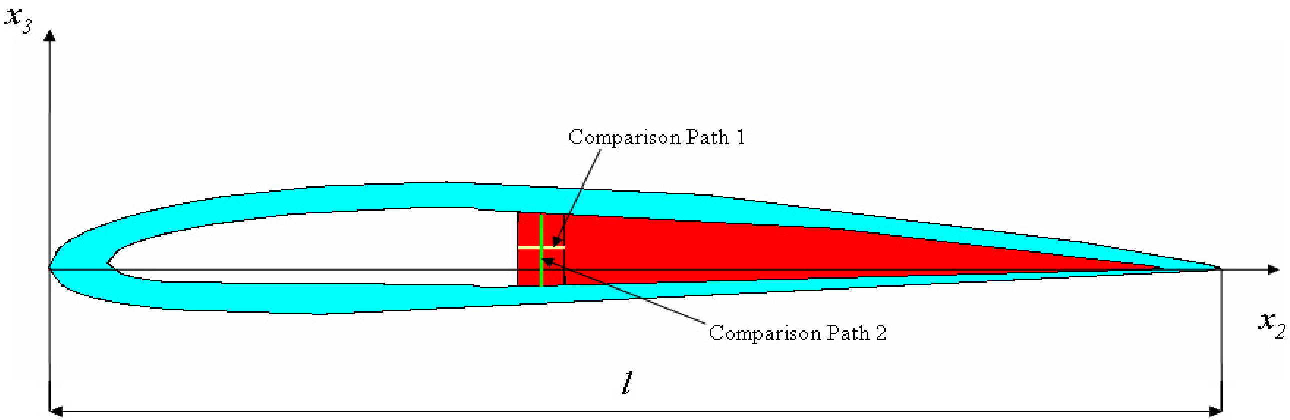
Realistic Rotor Blade



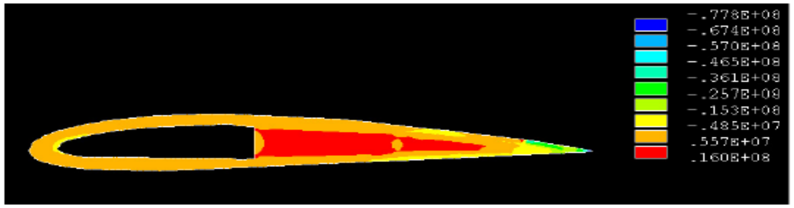
- Realistic rotor blade
- 100°C temperature increase
- Find thermal stress
- ANSYS model using brick elements (4.8M DOFs)

Wang, Q. and Yu, W.: “A Variational Asymptotic Approach for Thermoelastic Analysis of Composite Beams,” *Advances in Aircraft and Spacecraft Science*, vol. 1, 2014, pp. 93-123.

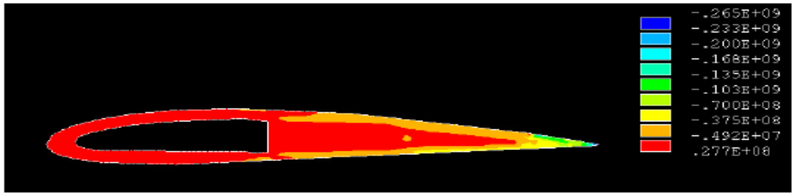
Realistic Rotor Blade



- σ_{11}

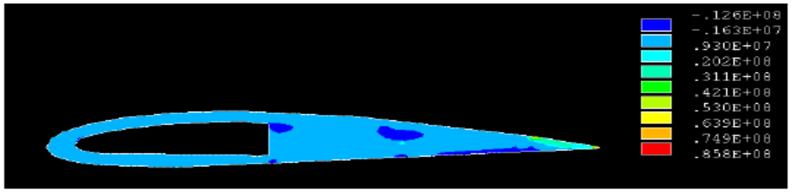


- σ_{22}

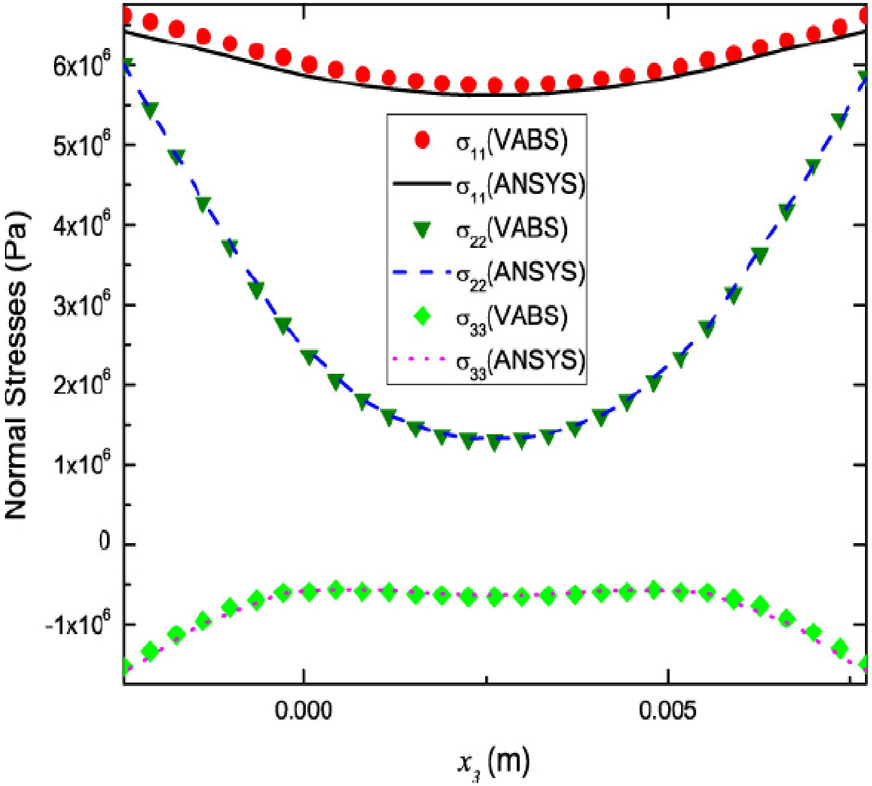


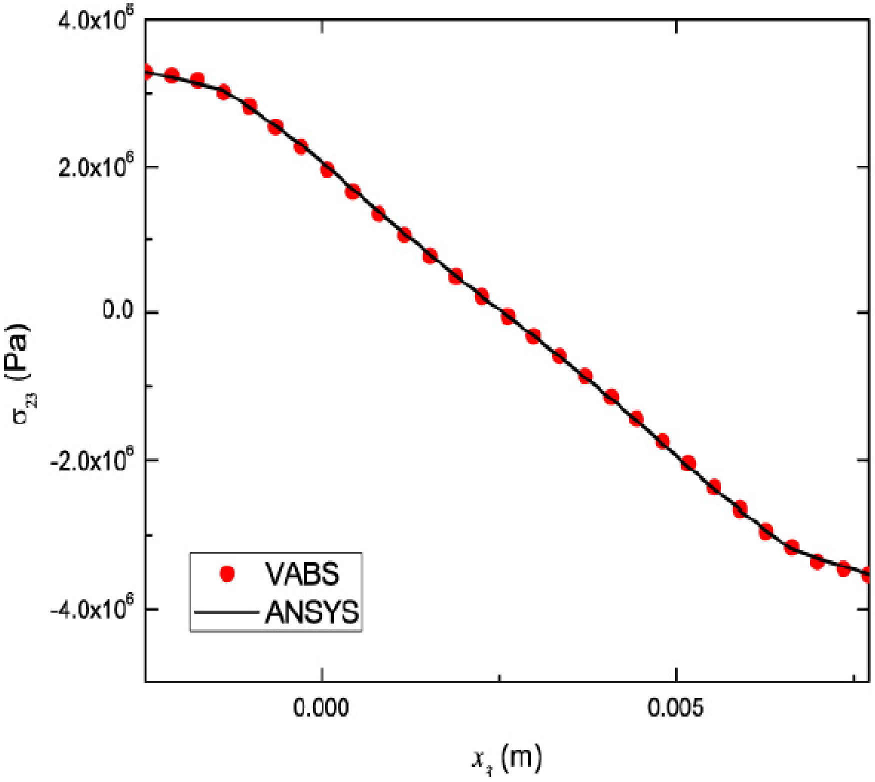
- σ_{33}

- σ_{23}

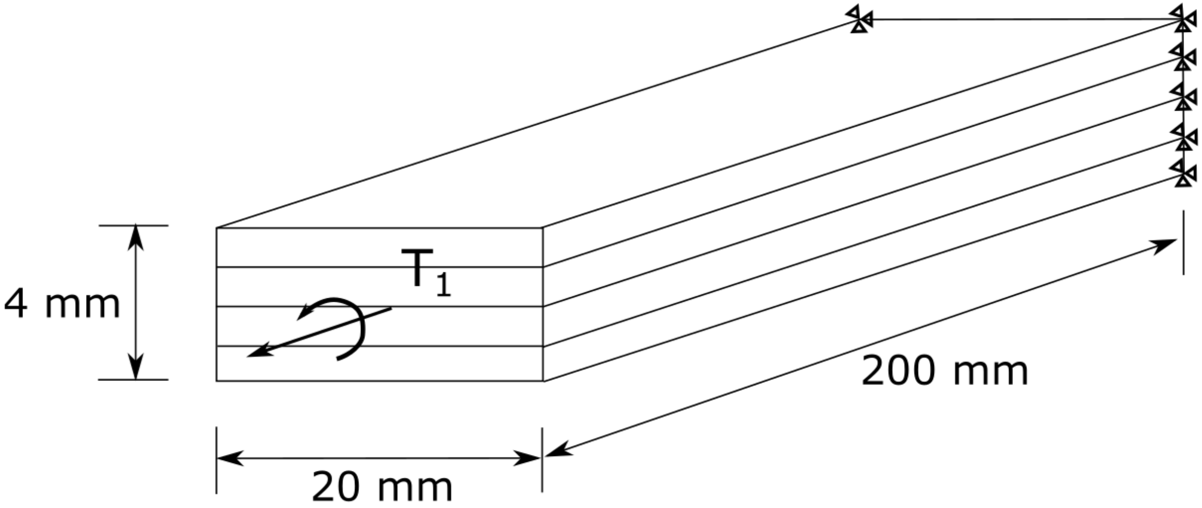


Realistic Rotor Blade





4-Layer Laminate Under Torque

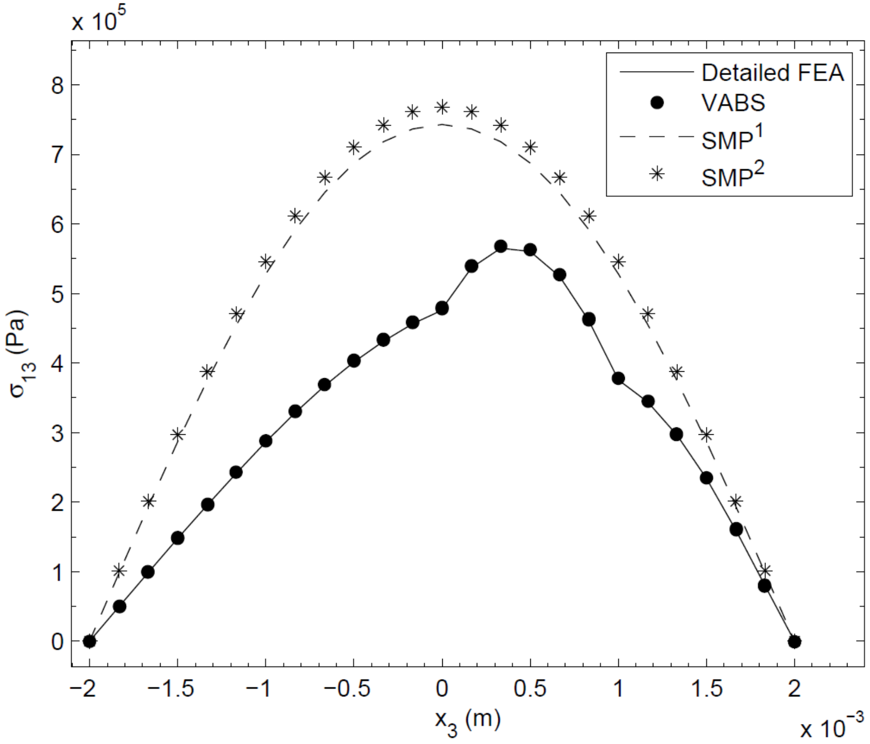


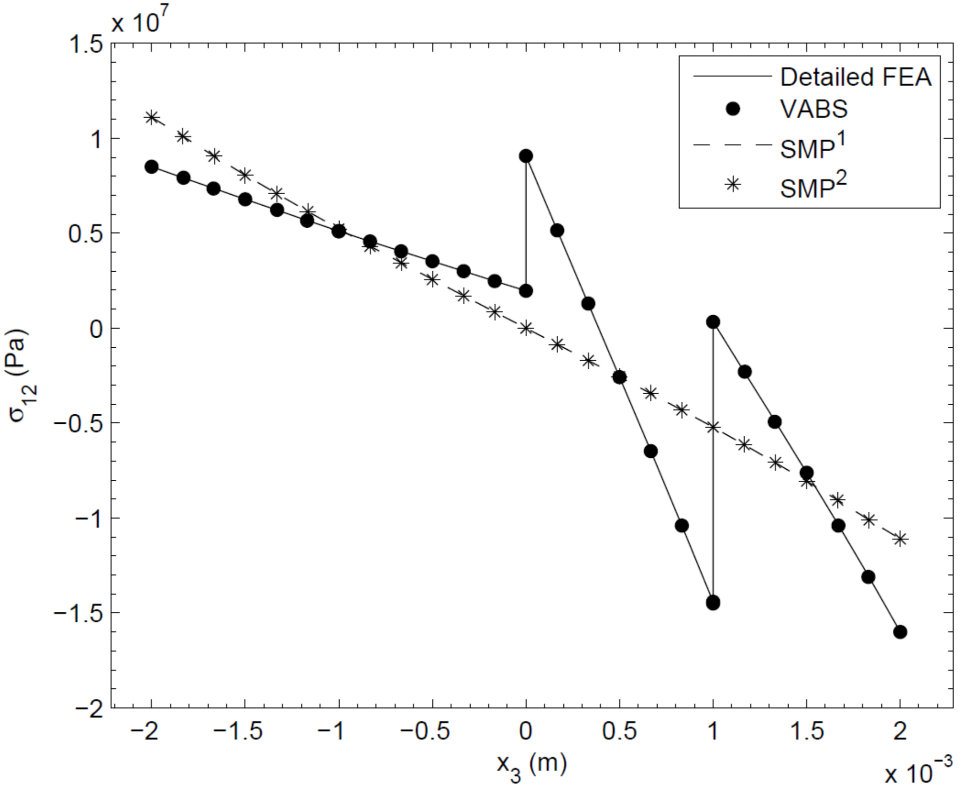
$$T_1 = 1 N \cdot m$$

Layup Sequence	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
$[0/90/\pm 45]$	132	10.8	10.8	5.65	5.65	3.38	0.24	0.24	0.59

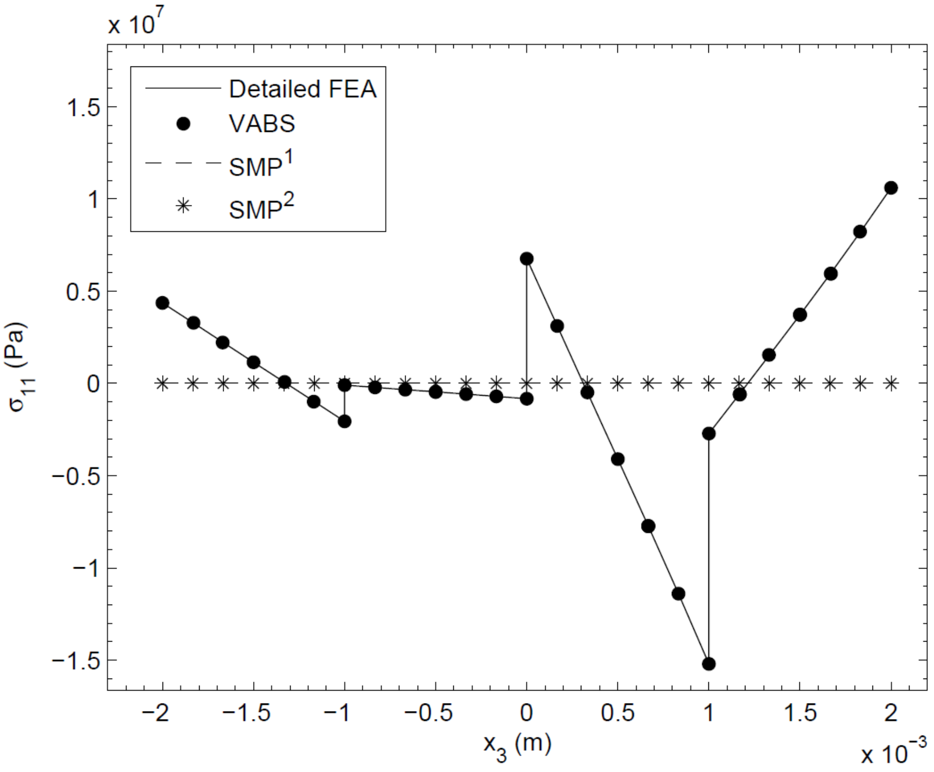
Liu, N. and Yu, W.: “Loss of Accuracy Using Smeared Properties in Composite Beam Modeling,” *Proceedings of the American Society for Composites 30th Technical Conference*, East Lansing, Michigan, Sept. 28-30, 2015.

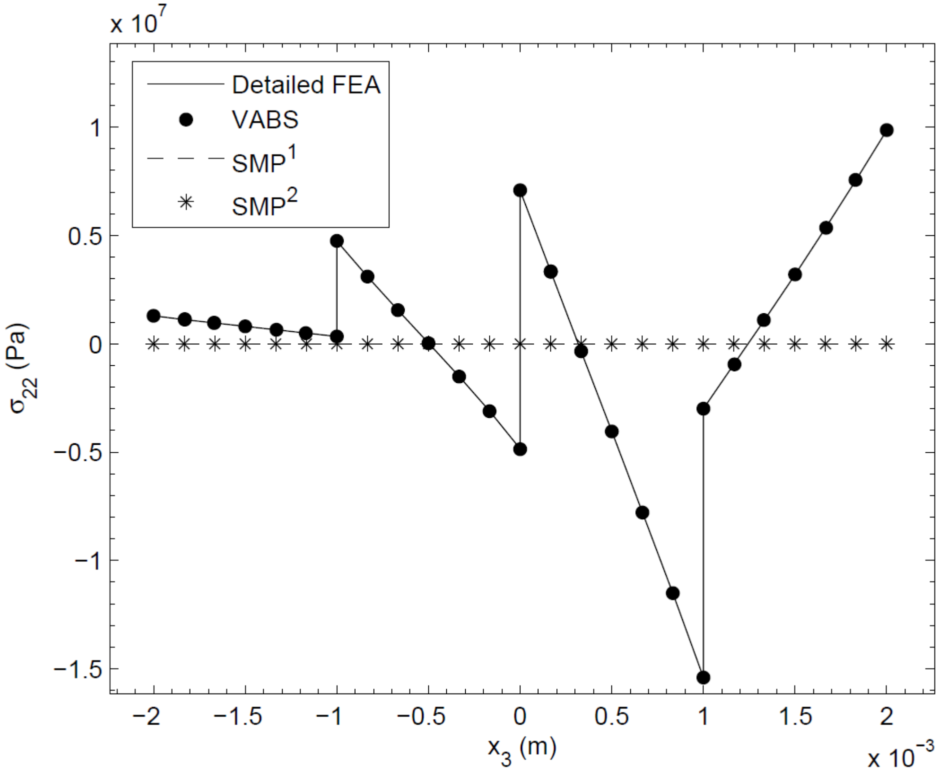
Loss of Accuracy Using Smeared Properties





Loss of Accuracy Using Smeared Properties





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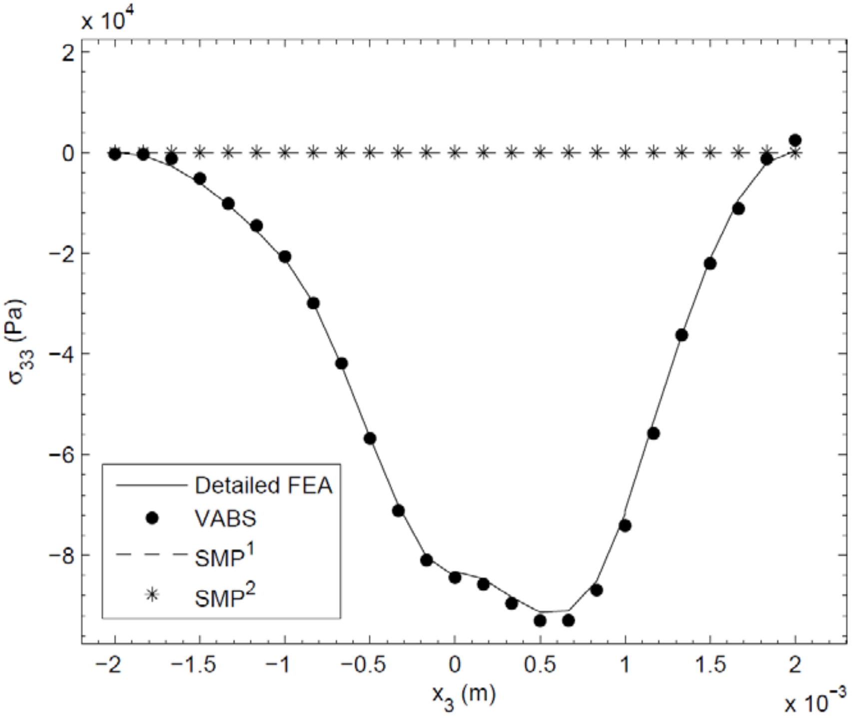
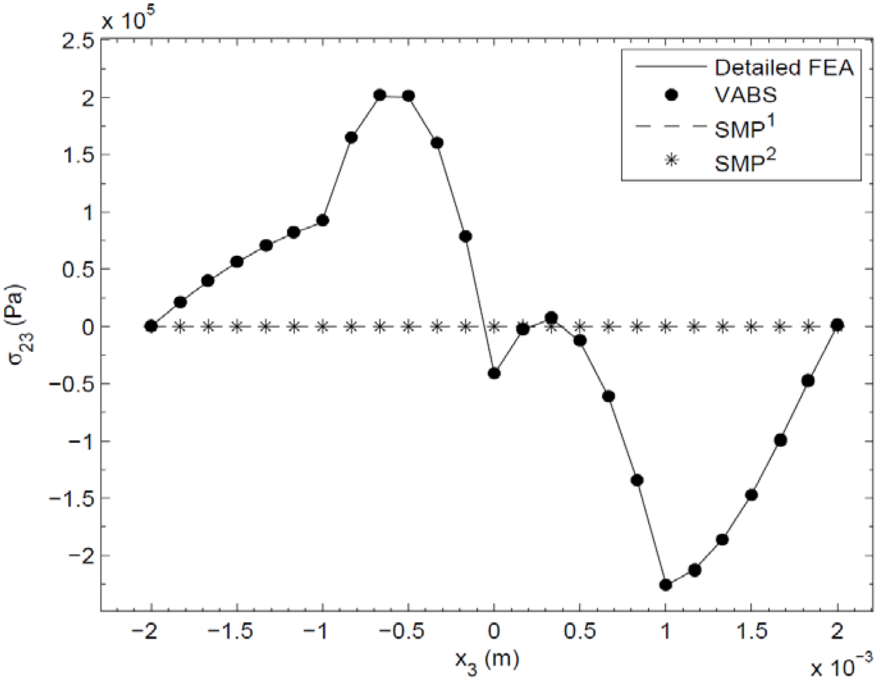
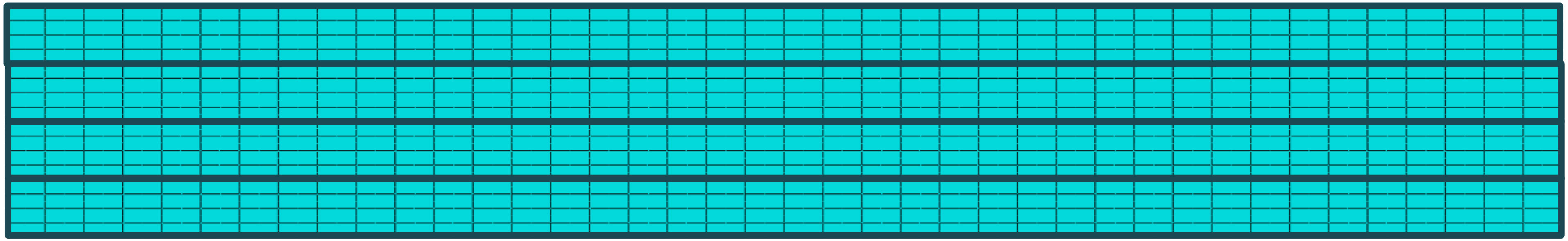
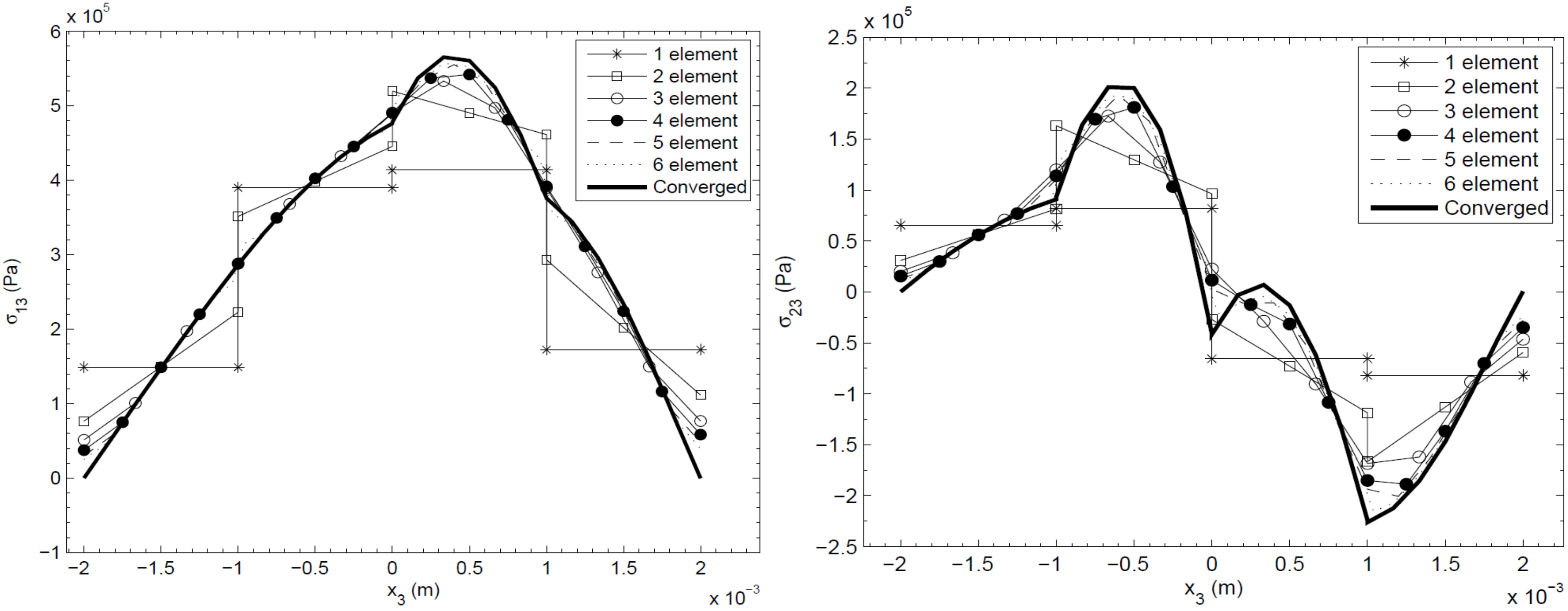




Elements/Layer Needed for Direct Numerical Simulation





Converged: six 20-noded brick elements/layer thickness.

Conclusion

- VABS: an efficient high-fidelity alterative of DNS for slender composite structures.
  - Best complete set of beam properties: needed for static/dynamic analysis using beam elements.
  - Complete set of accurate 3D fields.
  - Highly optimized for efficiency: ply-level details of real blades can be modeled in seconds
  - Extensively validated in helicopter and wind industry
  - Directly integrated into other design environments
  - An essential piece for multiscale simulation of slender composite structures to link properties predicted by micromechanics to structural analysis.