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Comparative Fluid-Structure Interaction Analysis of Solid and Hollow Core Blades in Full-Scale Reference Model 1 Tidal Turbine

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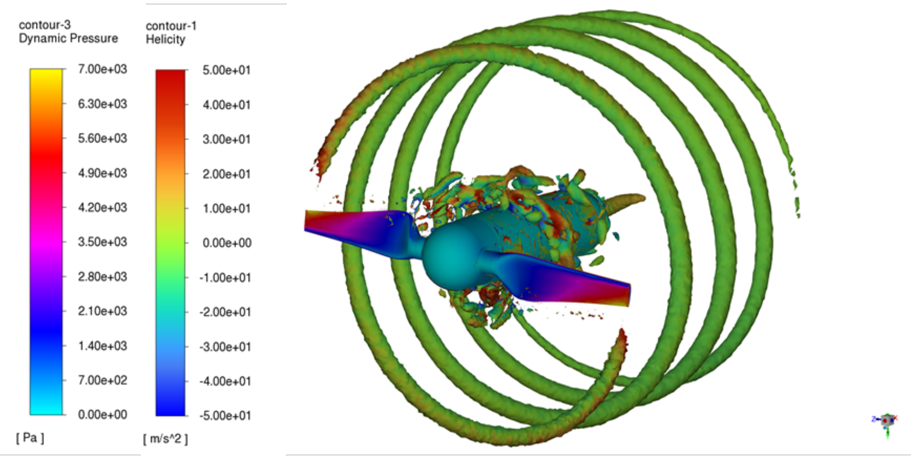
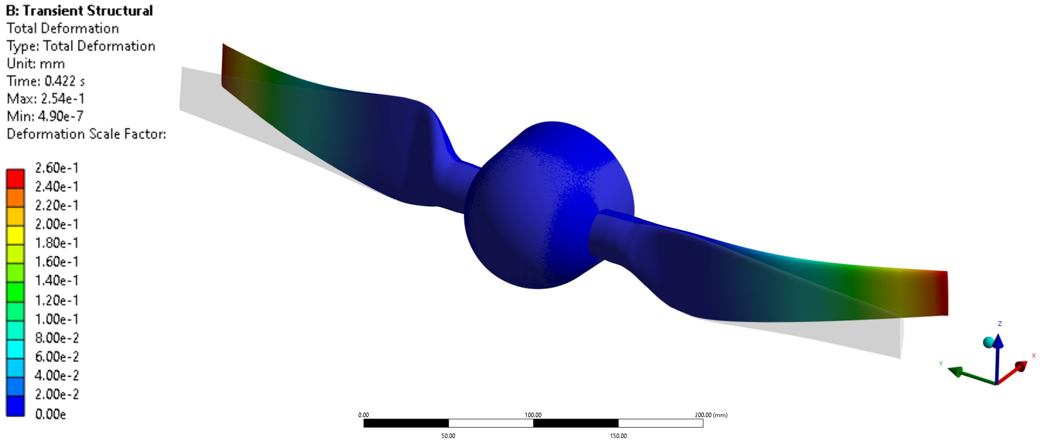
INTRODUCTION

- ✓ Tidal turbines must maintain performance and durability under diverse and demanding loading conditions.
- ✓ The complex interaction between turbulent water flow and blade structure induces significant stress, deflection, and fatigue, making accurate prediction of device reliability and Levelized Cost of Energy (LCOE) a critical challenge.
- ✓ Traditional one-way simulations, which separate fluid and structural analysis, often fail to capture the full picture.
- ✓ This study utilizes a two-way coupled Fluid-Structure Interaction (FSI) model, providing time-accurate solutions for the loading and performance of a deforming rotor, which is crucial for realistic performance prediction.
- ✓ By focusing on the full-scale RM1 tidal turbine, we explore these dynamics to enhance the design and efficiency of future marine energy systems.





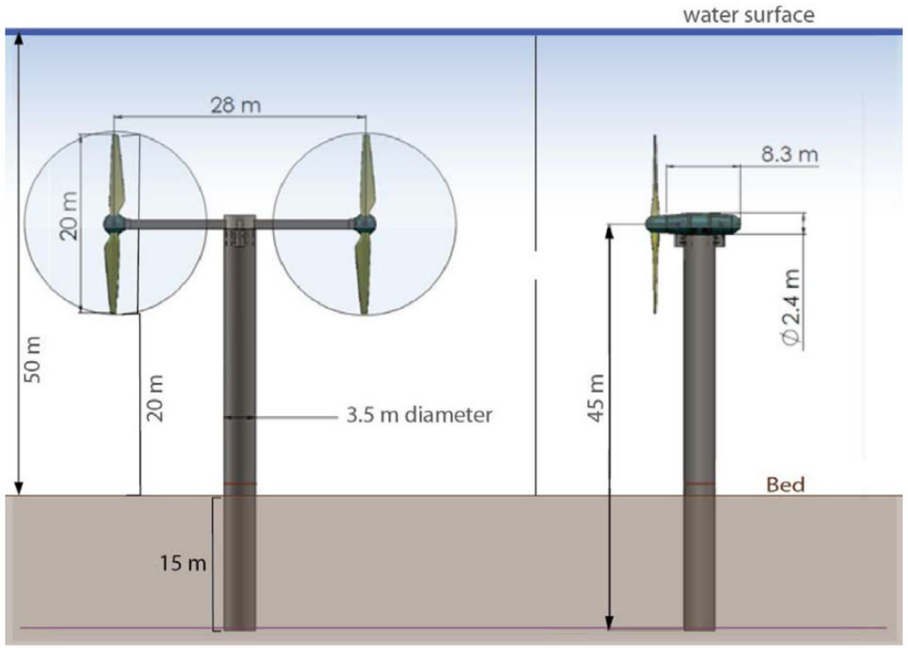
Q-criterion iso-surface colored by helicity and pressure contour on the turbine surface (left) and magnitude of total deformation of the rotor (right)

OBJECTIVES AND TARGET GEOMETRY MODEL

- ✓ Develop and verify a high-fidelity, two-way coupled FSI model for the full-scale RM1 tidal turbine.
- ✓ Compare the turbine's hydrodynamic performance (power, thrust) and structural response (deformation, stress) using both one-way and two-way FSI simulations to quantify the impact of fluid-structure coupling.
- ✓ Analyze and contrast the performance of solid vs. hollow core blade geometries to inform structural design and optimization.
- ✓ Demonstrate the necessity of two-way FSI for achieving accurate structural integrity assessments required for future LCOE analysis.

Reference Model 1 (RM1)

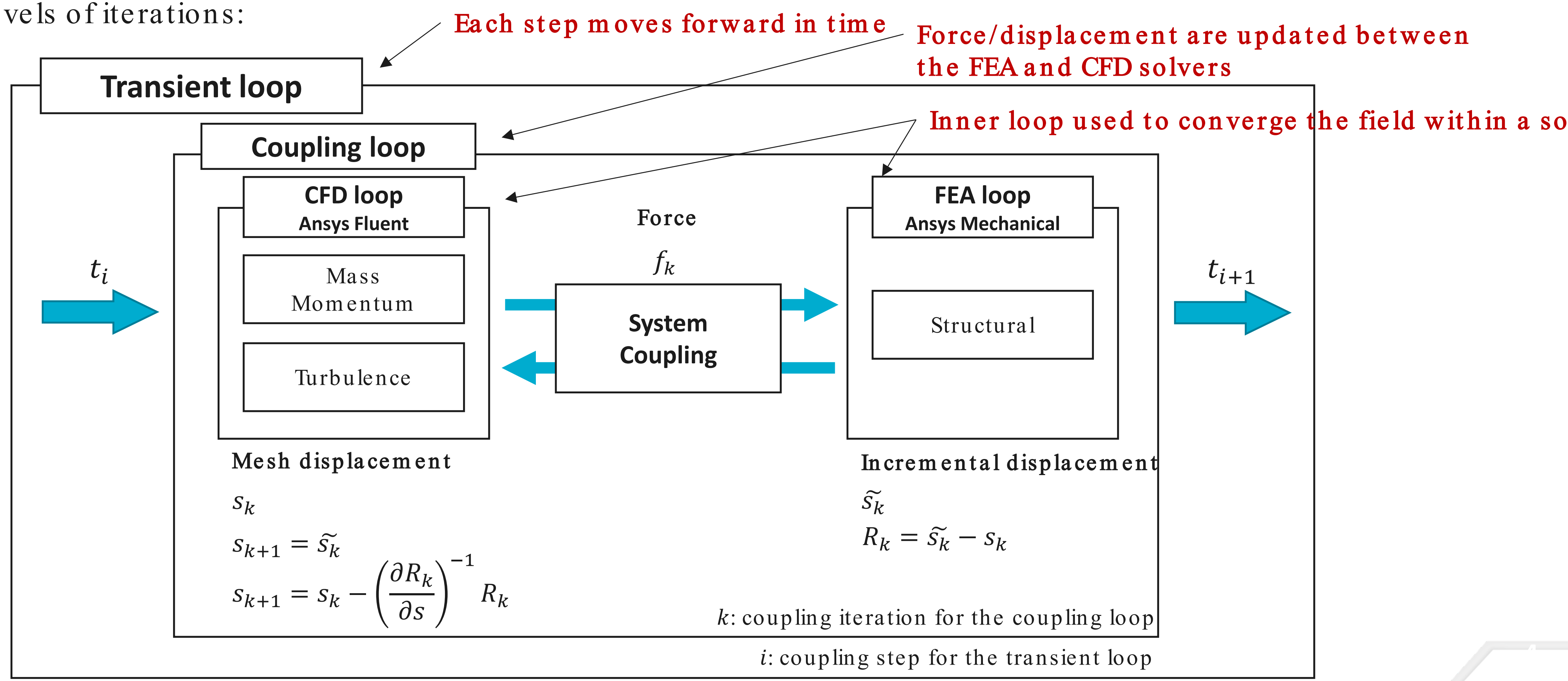
- Rotor diameter: 20m
- Rated current speed: 2.0 m/s
- Blade construction: The FSI model analyze three distinct blade configurations:
  - Solid core metal blade
  - Hollow core metal blade
  - Hollow core composite blade



TWO-WAY COUPLED FSI MODEL

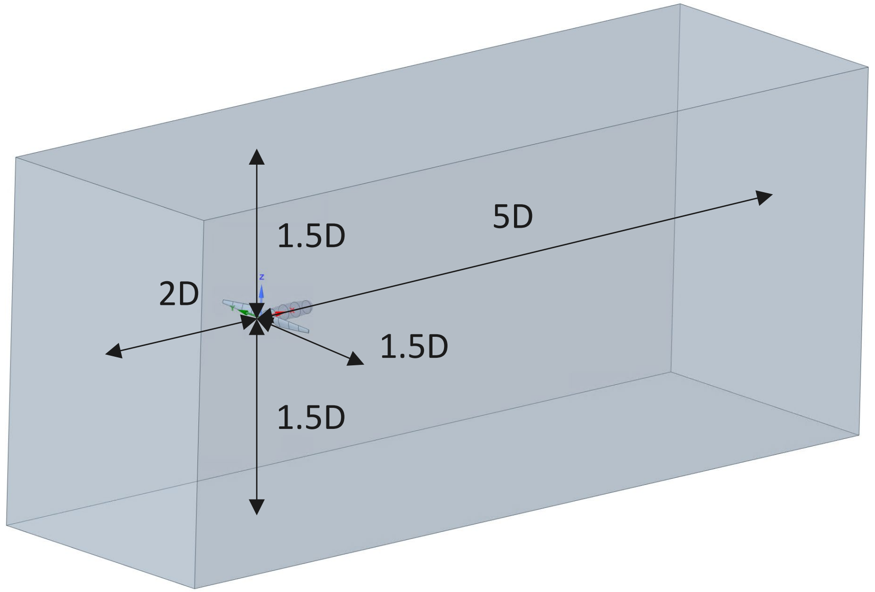
Two-way iteratively implicit approach (strong coupling)

- Iterate within each time step to obtain an implicit solution
- Three levels of iterations:



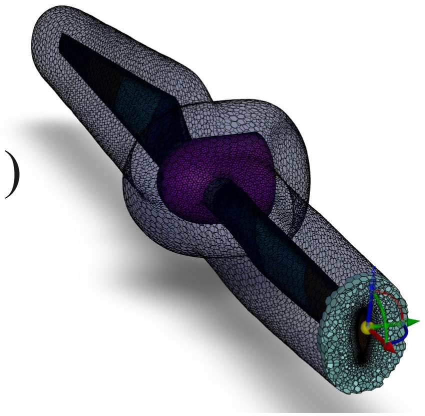
CFD MODELING

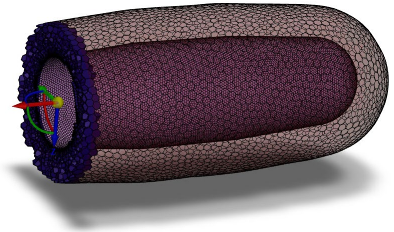
- Computational domain and boundary conditions
  - One rotor only
  - Cut off 1% of chord length for mesh quality
  - Blockage effect is ignored
  - (0, 0, 0,) at the nose of the rotor
  - Inlet: 2 m/s uniform flow
  - Outlet: zero gauge pressure
  - Symmetry: top and sides
  - No-slip wall: rotor, nacelle, and bottom

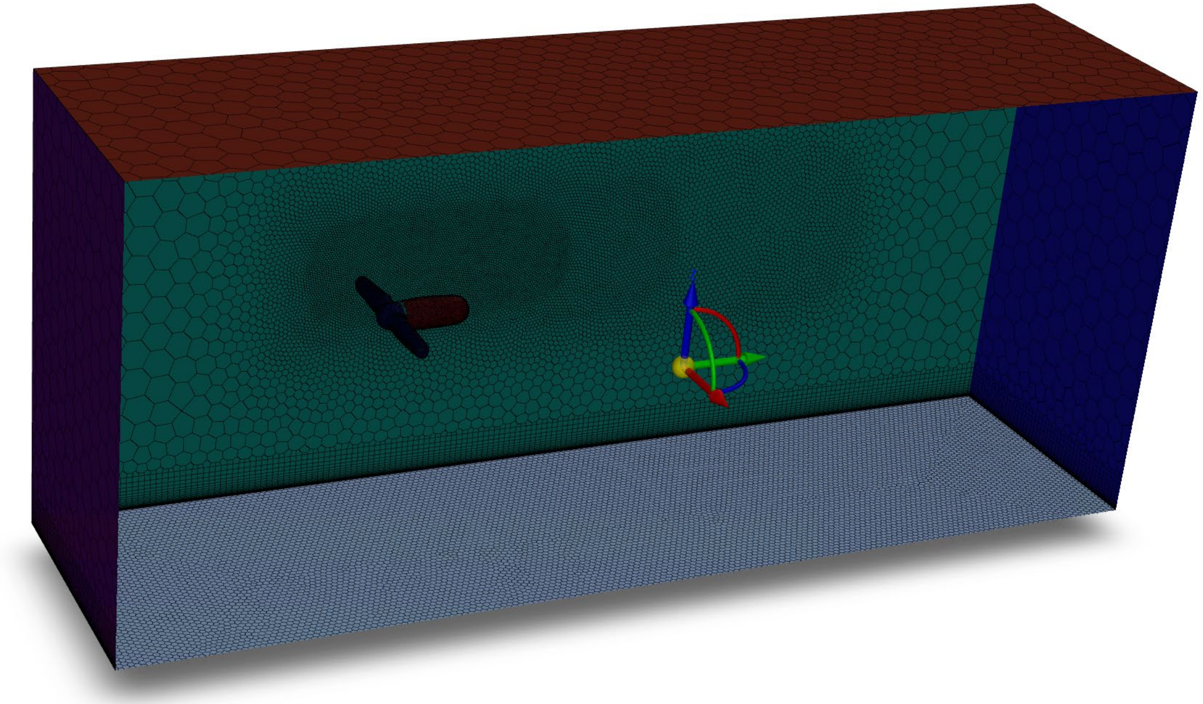


CFD MODELING

- Computational Mesh (Medium grid)
  - Polyhedral mesh with overset multi-blocks (# of cells)
    - Rotor: 5.88M
    - Nacelle: 1.02M
    - Bkg w/ refinement: 2.67M
    - Total: 9.57M
  - Prism layers on the rotor and nacelle wall
    - Target $y^+ = 30 - 50$





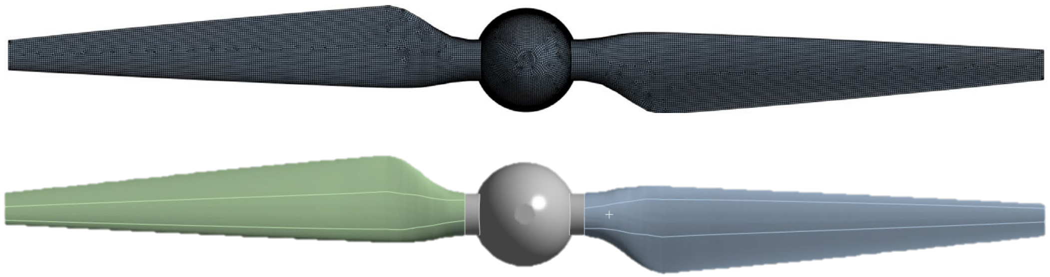


CFD MODELING

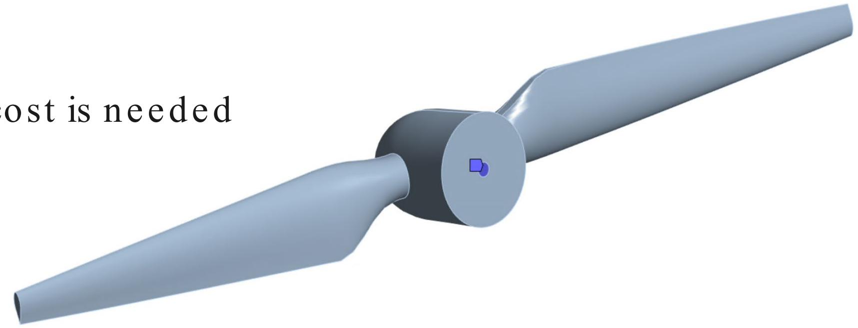
- Mathematical Model and Numerical Scheme
  - Viscous model:
    - Realizable $k - \epsilon$ model with wall function
  - Pressure-velocity coupling:
    - Pressure-based coupled solver
  - Spatial discretization:
    - Pressure: second order
    - Momentum: second order upwind
    - Turbulence model: second order upwind
  - Temporal discretization:
    - Transient formulation: first order implicit

FEA MODELING

- FEA Setup
  - Geometry and mesh
    - Rotor only
    - Hexahedral mesh with quadratic element order
    - Metal blades are modeled as a solid and hollow blade made from aluminum alloy 6061 T6
    - Hub is modeled as a solid for hollow metal and composite blade rotors

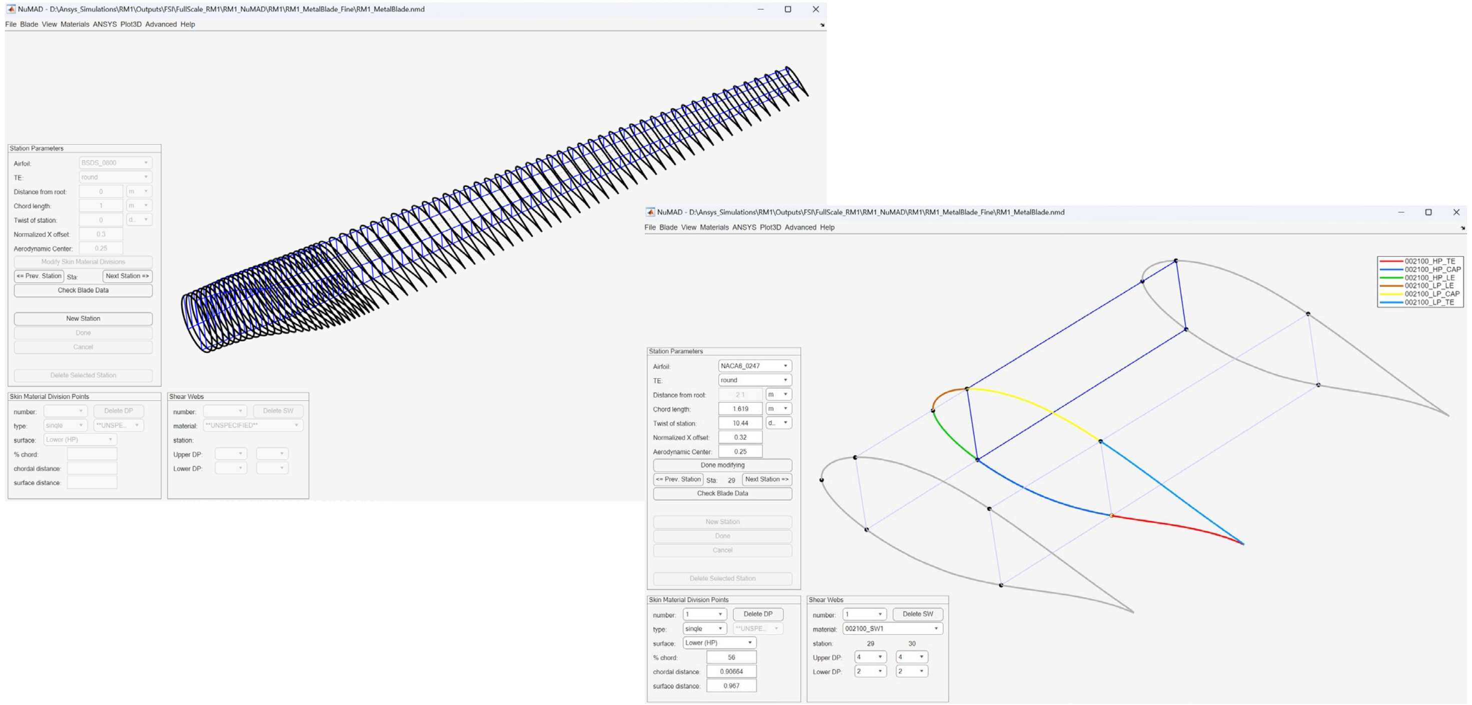


  - Boundary conditions
    - Assigned angular velocity corresponding to the turbine rotating speed
    - Fixed support at the rotor hub center
      - Without modeling actual rotation of rotor in FEA side, lower computation cost is needed

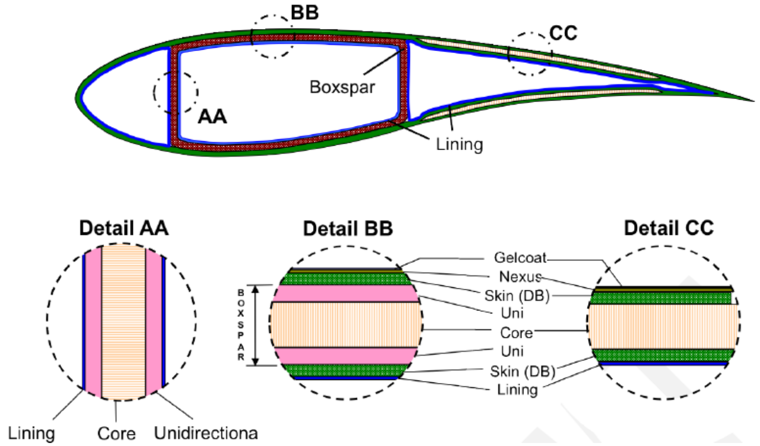


FEA MODELING

- Modeled hollow metal and composite blades with shear webs leveraging NuMAD
  - The blade is divided into spanwise 74 stations.
  - Each station includes 5 division points, defining 8 sections for assigning material layups.
  - Material stacking sequences and geometry definitions are referenced from Lawson et al. (2012).
  - Shear webs are positioned at 12.8% and 56.0% of the local chord length.



3D model of the RM1 turbine blade with shear webs generated using NuMAD (top), and skin material segmentation at station 29 (bottom)

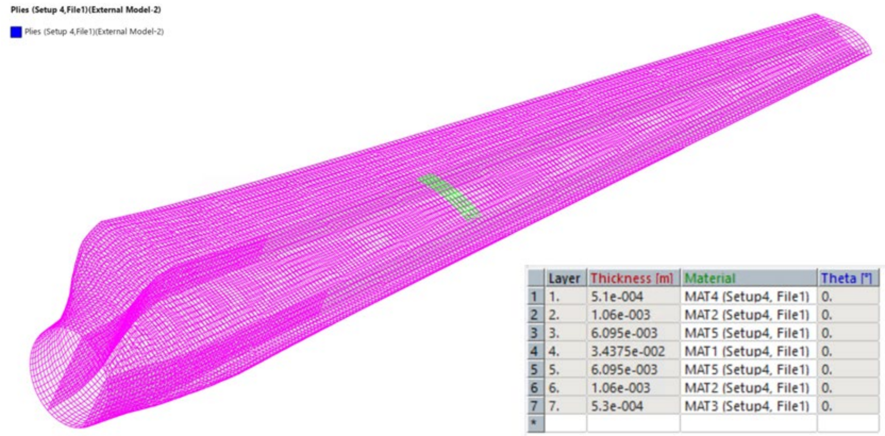


Material	tply (mm)	ρ (Kg/m3)	E (Pa)	G (Pa)	σ (Pa)	σ (Pa)
Gelcoat	0.381	1664	--	--	--	--
Nexus	0.51	1830	--	--	--	--
Double-bias	0.53	1830	1.03E+10	8.00E+09	151	-174
Lining	0.53	1830	1.03E+10	8.00E+09	151	-174
Unidirectional	0.53	1860	3.70E+10	4.10E+09	986	-746
Core	3.125	128.1	--	--	--	--

Representative structural layup of composite laminates at a typical blade section (adapted from Lawson et al., 2012)

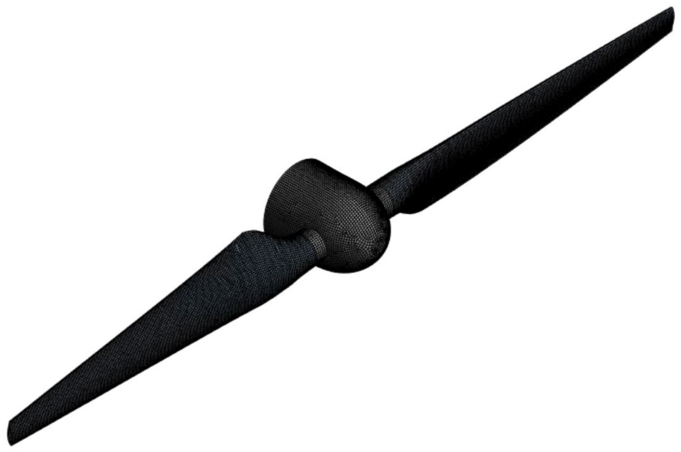
FEA MODELING

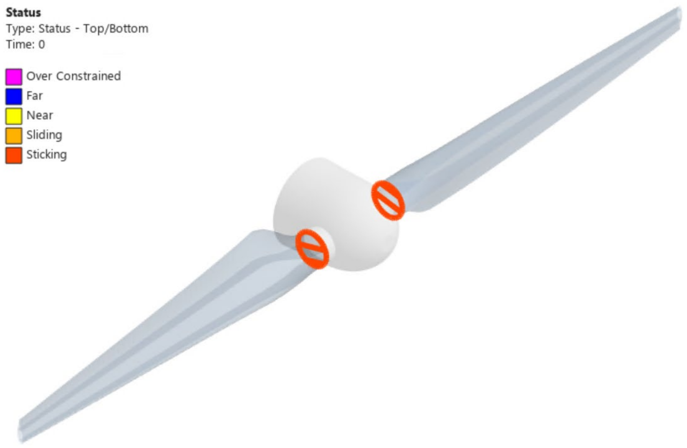
- Converted NuMAD blade model for import into ANSYS Mechanical
  - Blade shell geometry and composite ply information successfully imported into the structural FEA environment
  - Rotor hub and blade root modeled as solid parts
  - Hub–blade connection modeled as bonded (no separation or sliding)



	Layer	Thickness [m]	Material	Theta [°]
1	1.	5.1e-004	MAT4 (Setup4, File1)	0.
2	2.	1.06e-003	MAT2 (Setup4, File1)	0.
3	3.	6.095e-003	MAT5 (Setup4, File1)	0.
4	4.	3.4375e-002	MAT1 (Setup4, File1)	0.
5	5.	6.095e-003	MAT5 (Setup4, File1)	0.
6	6.	1.06e-003	MAT2 (Setup4, File1)	0.
7	7.	5.3e-004	MAT3 (Setup4, File1)	0.
*				

Imported composite layup configuration in ANSYS Mechanical and material stack details at a section

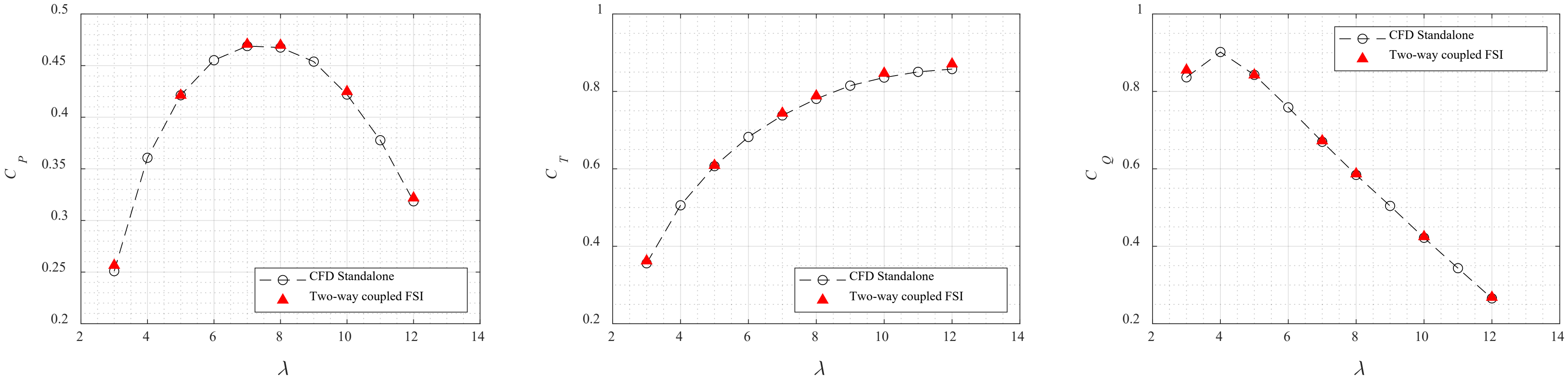




FEA mesh of full-scale hollow RM1 rotor blade (left) and contact surface boundary condition (right)

SIMULATION RESULTS – SOLID METAL BLADE

CFD vs Two-way coupled FSI



TSR	C_P			C_T			C_Q		
	CFD	FSI	Diff.	CFD	FSI	Diff.	CFD	FSI	Diff.
3.0	0.251	0.257	2.23 %	0.356	0.362	1.75 %	0.836	0.855	2.23 %
5.0	0.421	0.421	-0.01 %	0.607	0.609	0.33 %	0.843	0.843	-0.01 %
7.0	0.469	0.471	0.37 %	0.738	0.744	0.78 %	0.670	0.672	0.37 %
8.0	0.468	0.470	0.46 %	0.781	0.788	0.98 %	0.584	0.587	0.46 %
10.0	0.422	0.425	0.68 %	0.836	0.847	1.32 %	0.422	0.425	0.68 %
12.0	0.319	0.322	1.02 %	0.858	0.871	1.55 %	0.265	0.268	1.02 %

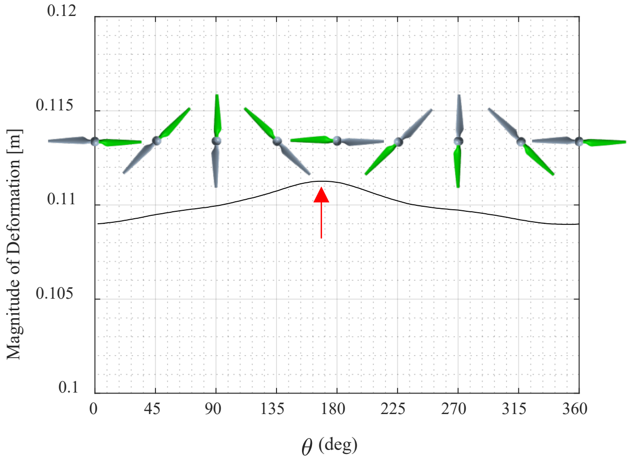
The low rotational speed introduces numerical errors in modeling the buffer layer of the boundary layer over the rotor due to the use of wall functions for computational efficiency.

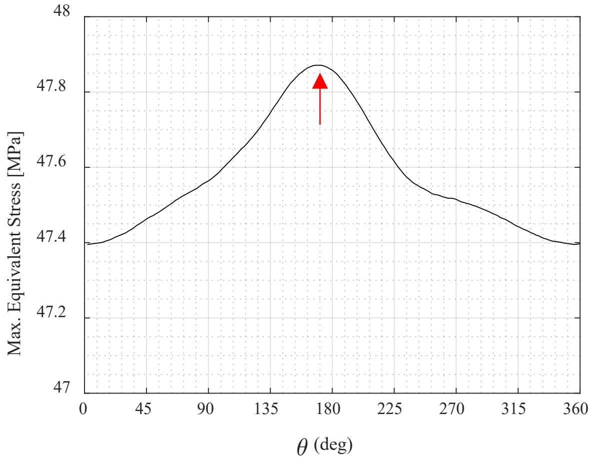
Power, thrust, and torque coefficient estimated from CFD stand alone and two-way coupled FSI simulations

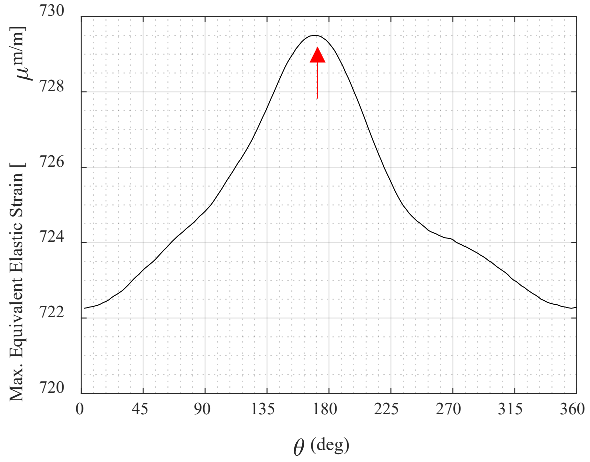
SIMULATION RESULTS – SOLID METAL BLADE

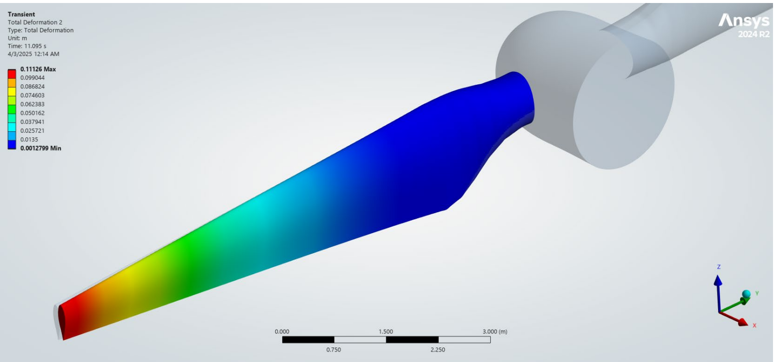
Structural response @ TSR = 7.0 (BOP)

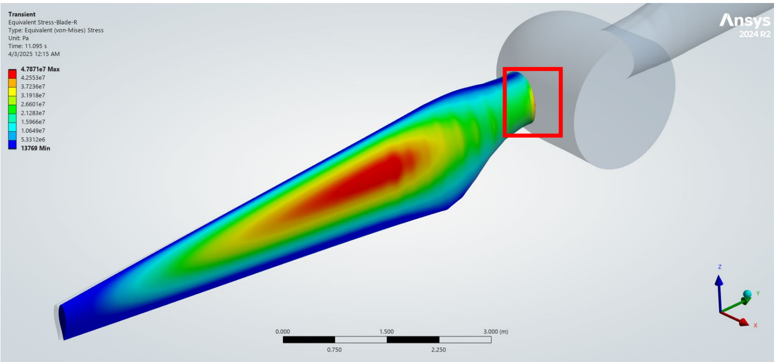
@ BOP (TSR = 7.0)	Max. Magnitude of total deformation (m)	Max. Equivalent Stress (MPa)	Max. Equivalent Elastic Strain (μm/m)
One-way FSI	0.1016	45.72	674.79
Two-way FSI	0.1113	47.87	730.49
Diff.	5.91 %	4.50 %	7.64 %

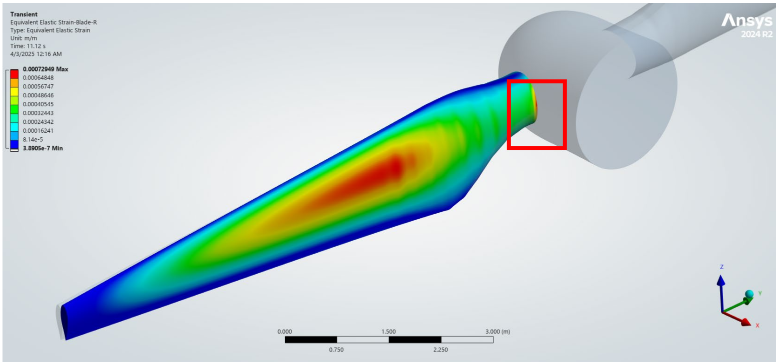






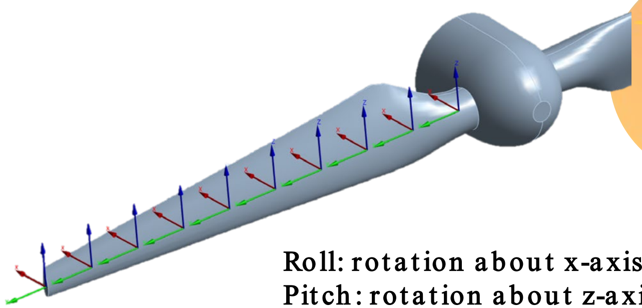




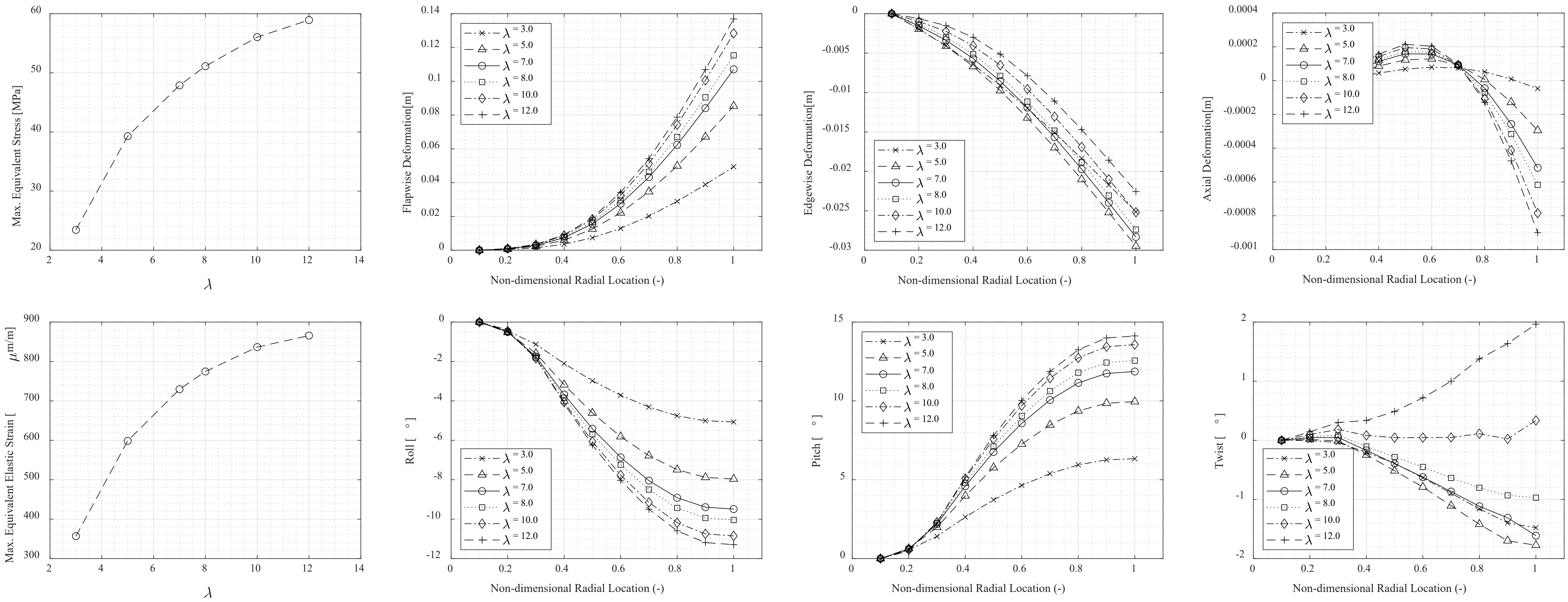


SIMULATION RESULTS – SOLID METAL BLADE

Maximum structural response at various TSRs



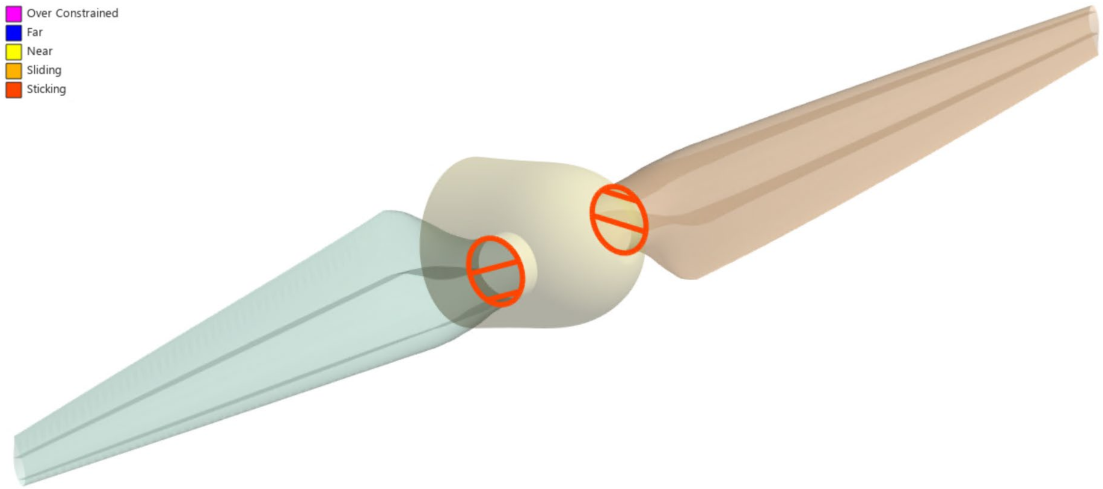
Roll: rotation about x-axis (flapwise direction)
Pitch: rotation about z-axis (edgewise direction)
Twist: rotation about y-axis (spanwise direction)



HOLLOW METAL BLADE MODEL

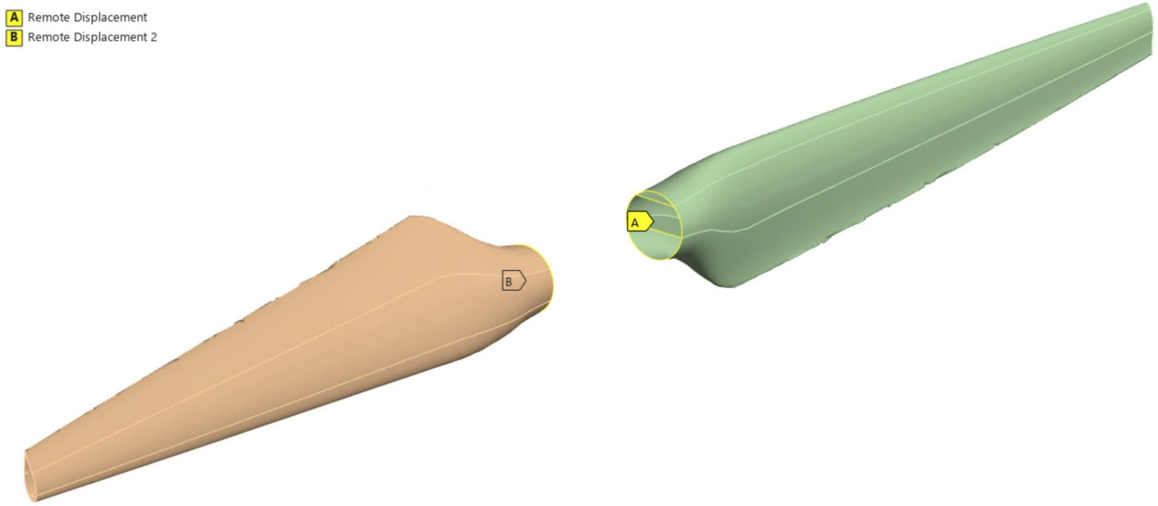
Full Model

- Hollow metal blade + Hub
- Direct connection between solid hub and shell blade geometries
- Predicts the stress concentration at the blade-hub interface



Simplified Model

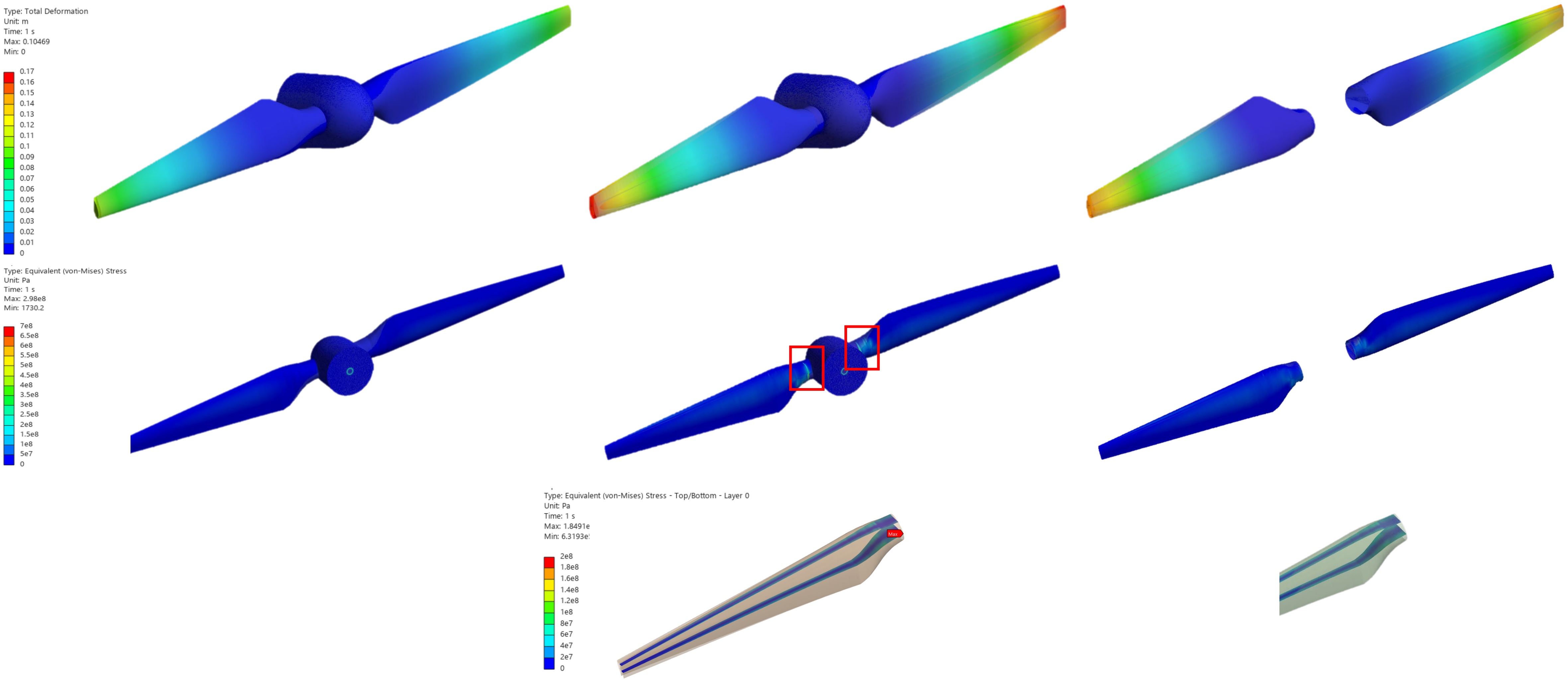
- Hollow metal blade only
- Remote displacement at blade root
- Cannot capture the local peak stress at the connection



SIMULATION RESULTS –METAL BLADE 1-WAY FSI

Structural response @ TSR = 7.0 (BOP)

Full Solid Blade Model | Full Hollow Blade Model | Hollow Blade Only



CONCLUSIONS

- High-Fidelity FSI Model:
  - Successfully developed and verified a two-way coupled FSI model on the solid metal blade, proving its necessity for accurate structural assessment over one-way analysis.
- Hollow Blade Workflow:
  - Established a workflow for modeling complex hollow blades by integrating NuMAD with ANSYS Mechanical.
- Identified Key Challenge:
  - Analysis of the hollow metal blade revealed a critical stress concentration at the solid-to-shell transition near the hub.
- Diagnosed Composite Instability:
  - The large stiffness difference between the hub and the highly flexible composite blade was identified as the source of numerical non-convergence.

FUTURE WORK

- Resolve Stress Concentration:
  - Modify the solid root geometry in CAD to create a gradual, tapered stiffness transition, mimicking composite ply drop-offs.
- Extend FSI Analysis:
  - Apply the validated two-way FSI simulation to the optimized hollow metal and composite blade models.
- Compare All Designs:
  - Conduct a final performance and structural reliability comparison of the solid, hollow metal, and composite blades.
- Inform LCOE:
  - Use the final, comprehensive dataset to inform future design optimization and Levelized Cost of Energy (LCOE) analysis.