SAND2011-6966C

A Sensitivity based Approach to SHM and Prognostics of Offshore Wind Turbines with Trailing Edge Disbonds

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[2]ATA Engineering

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NNSA National Nuclear Security Administration
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Background

- Operations and maintenance (O&M) costs for offshore wind plants are expected to be 2-3x higher than for onshore plants and represent 20-30% of the total levelized cost of energy [1]
  - Increased loading and environmental harshness
  - Difficulty of access


[2]

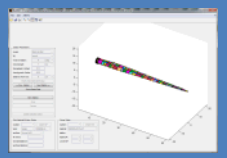
- Condition monitoring of offshore turbines as part of a condition based maintenance paradigm could provide significant cost reductions
  - Less regular maintenance
  - Decrease unscheduled maintenance
  - Improve supply chain management
  - Smart turbine load management
    - Operate and maintain turbines to maximize overall profit


[3]

Approach: Simulation Methodology

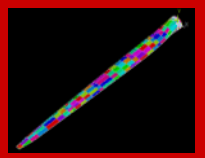
Healthy / Damaged Blade Model

(ANSYS)



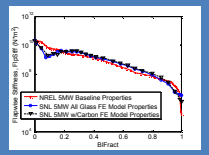
High Fidelity Simulations

(ANSYS)



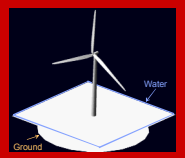
Equivalent Blade Model

(SNL BPE)



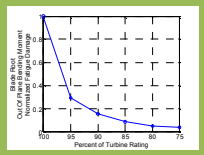
Full Turbine Simulations

(NREL FAST)



Damage Mitigating Control

(FAST)



Local Sensitivity

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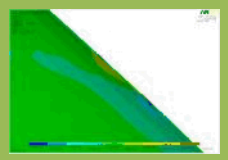
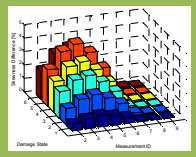


Offshore Turbine Model

(NREL 5MW)

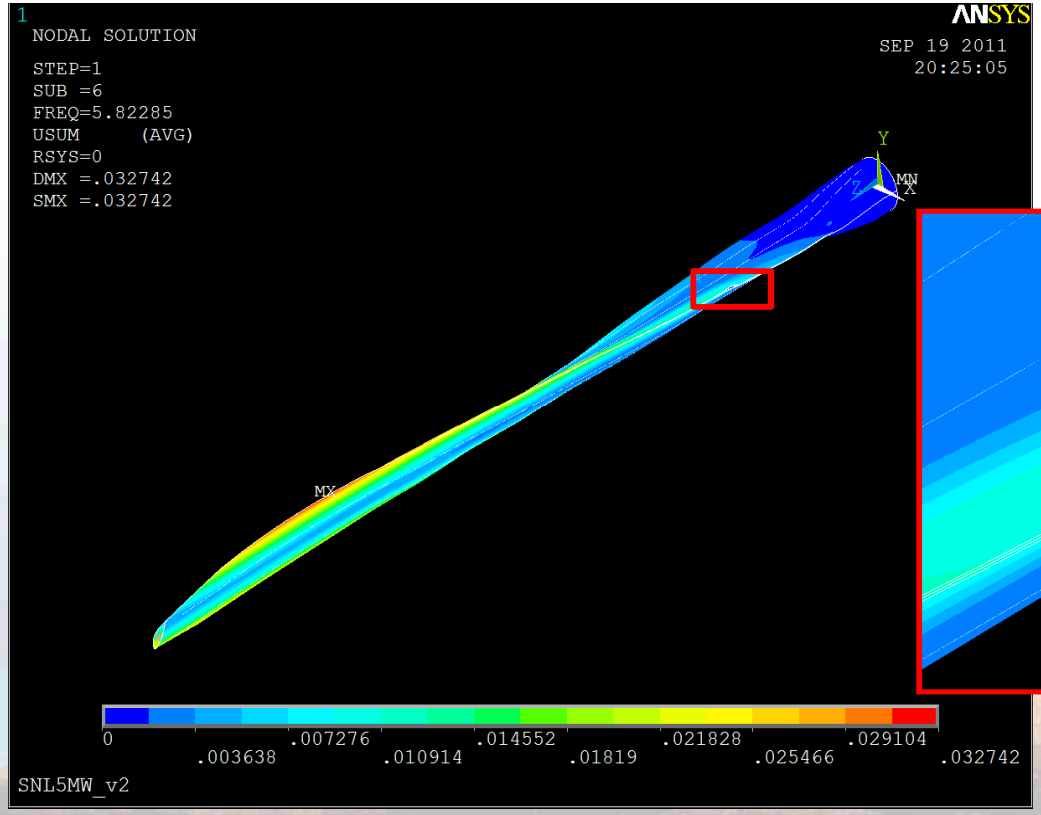
Global Operating Sensitivity

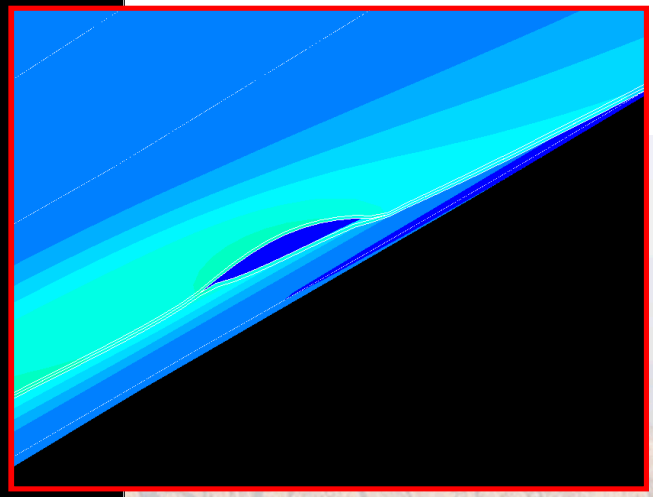
(ANSYS)



Healthy/Damage Blade Model

- Blade models with variable length trailing edge disbonds created





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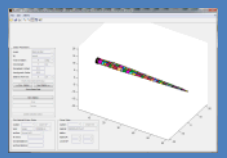

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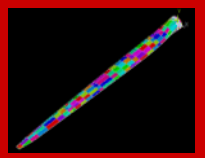

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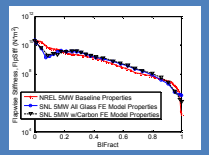

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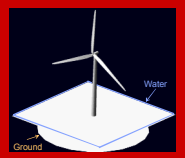

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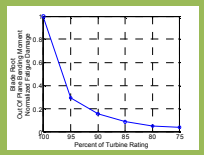

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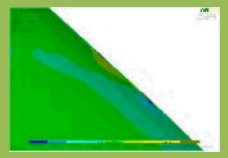

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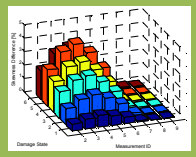
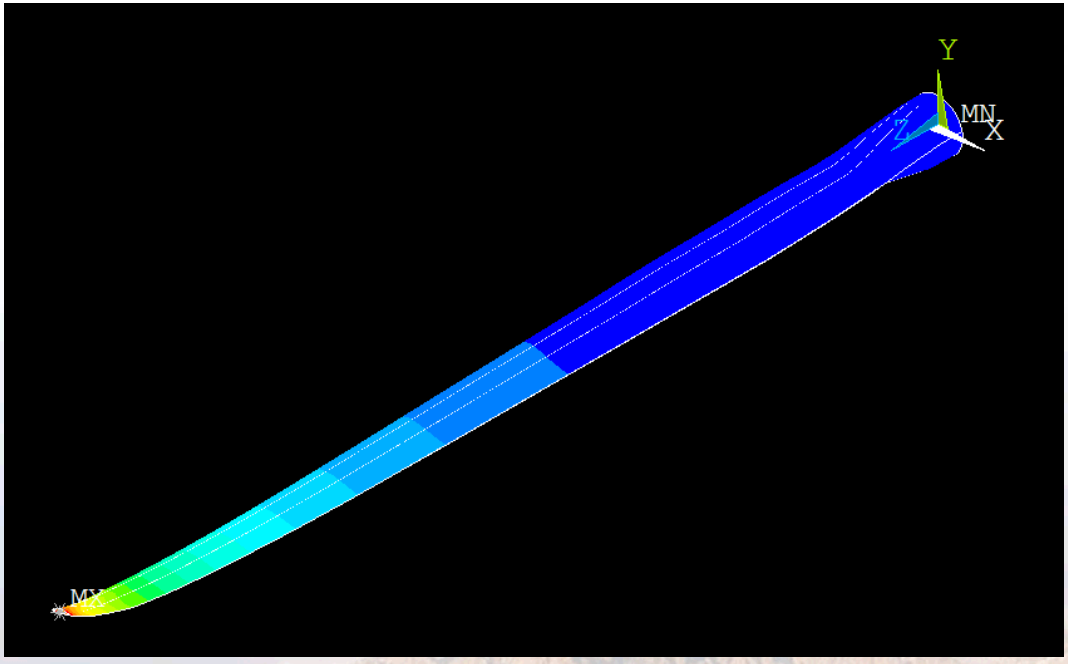


Reduced Order Blade Models

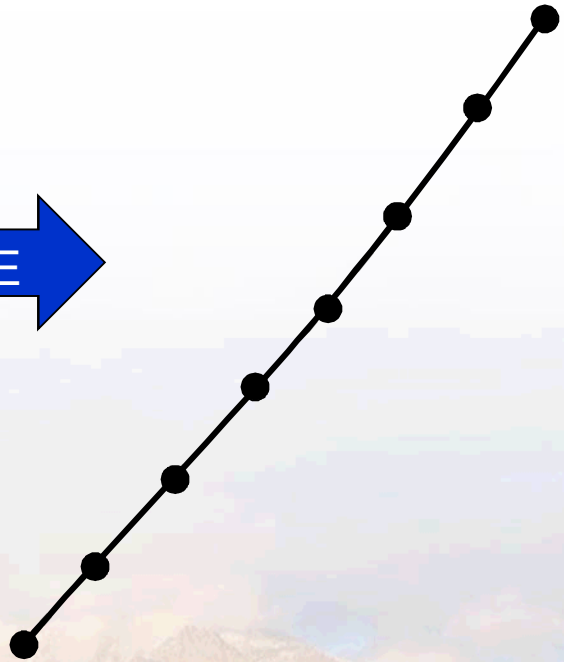
- High fidelity blade models reduced to equivalent beam elements for full turbine simulations

10s to 100s of thousands of DOF



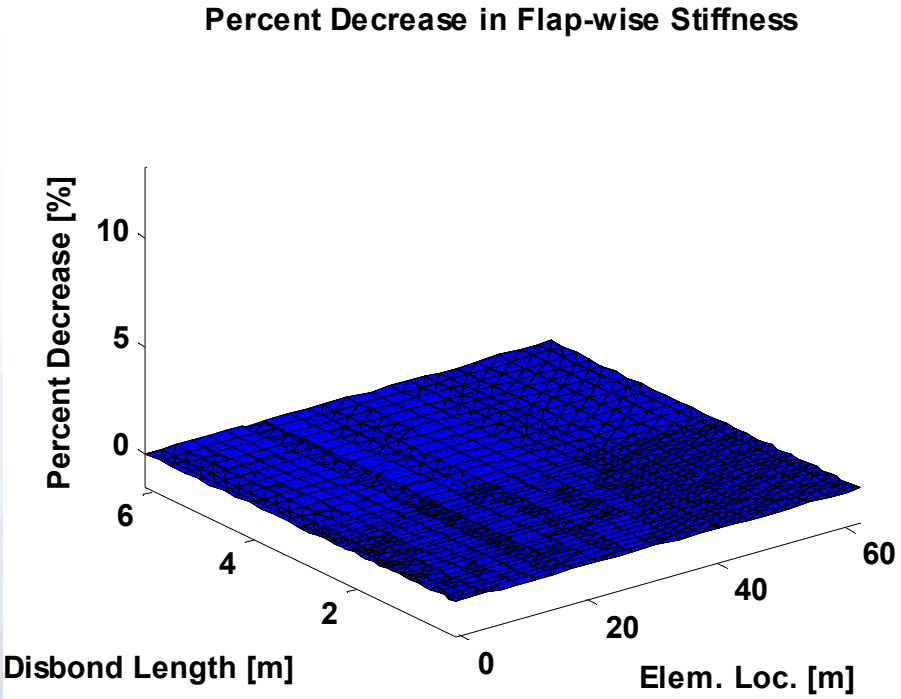
BPE

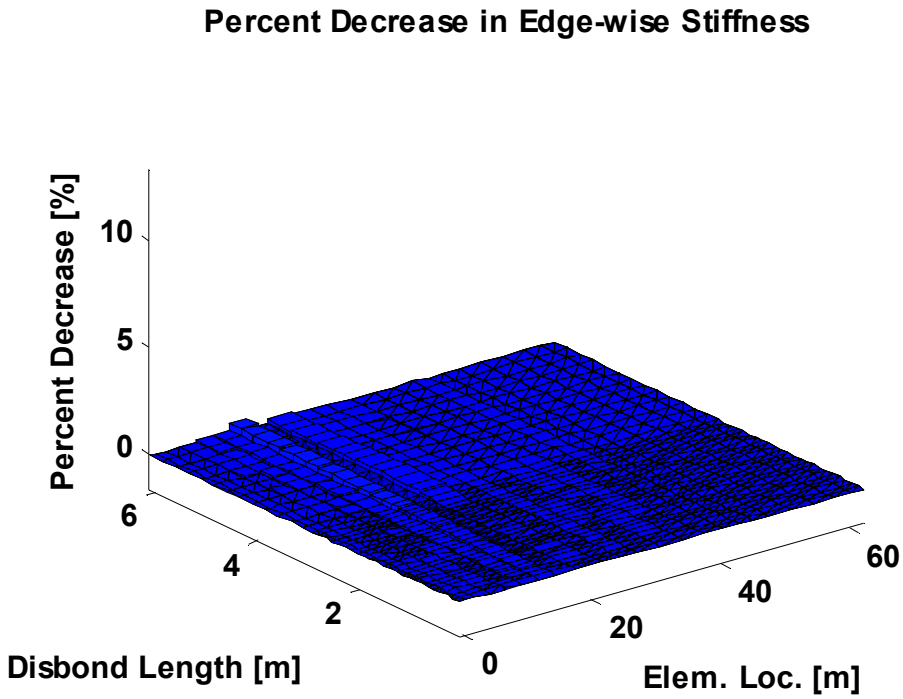
100s of DOF



Stiffness Changes due to Trailing Edge Disbonds

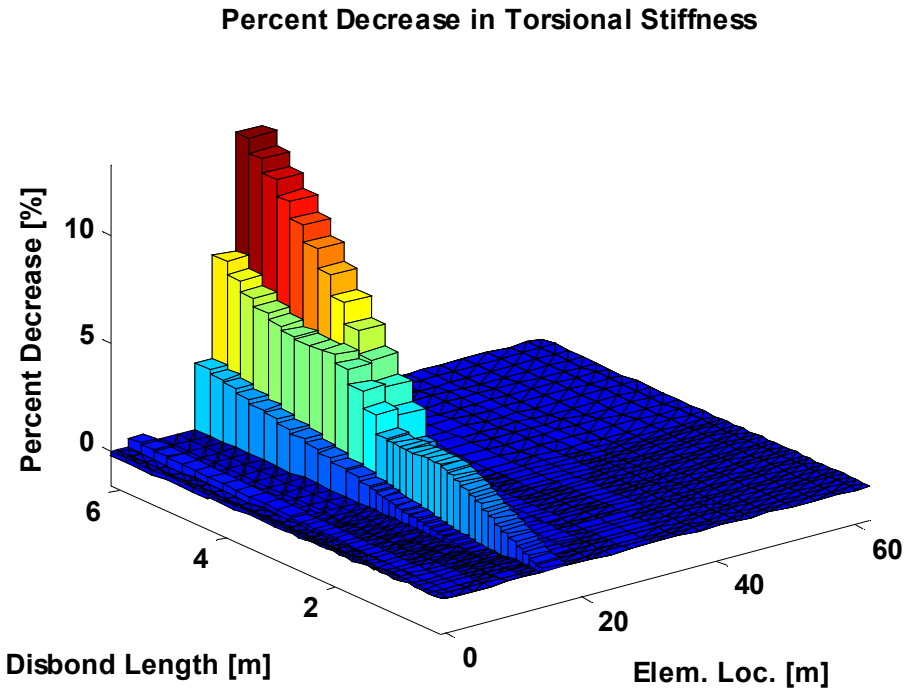
- 6 meter long disbond caused percent decreases of less than 0.5%

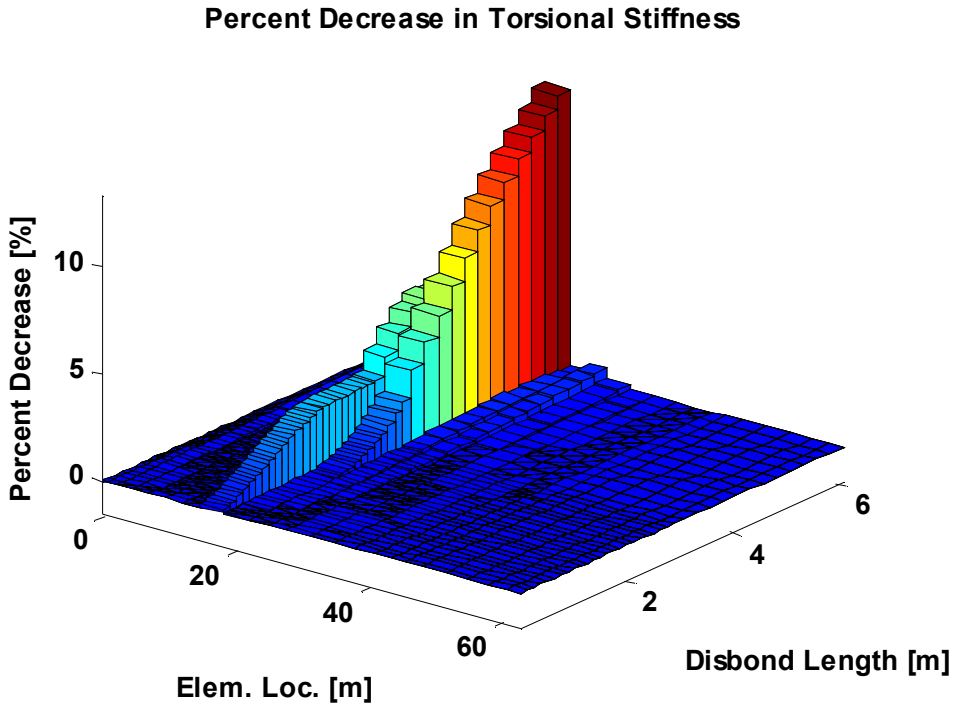




BPE Stiffness Changes due to Trailing Edge Disbonds

- A decrease of over 1% seen in a blade section for the 0.75 m disbond
- For the 6 m disbond two sections have decreases larger than 7.5%, max=13.3%





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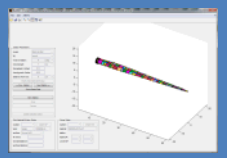

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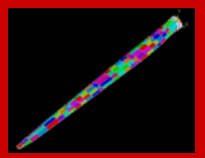

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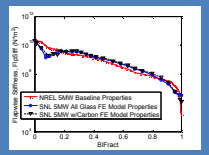

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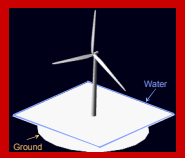

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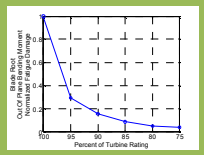

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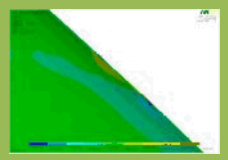

Offshore Turbine Model

(NREL 5MW)

Global Operating Sensitivity

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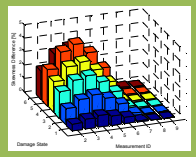
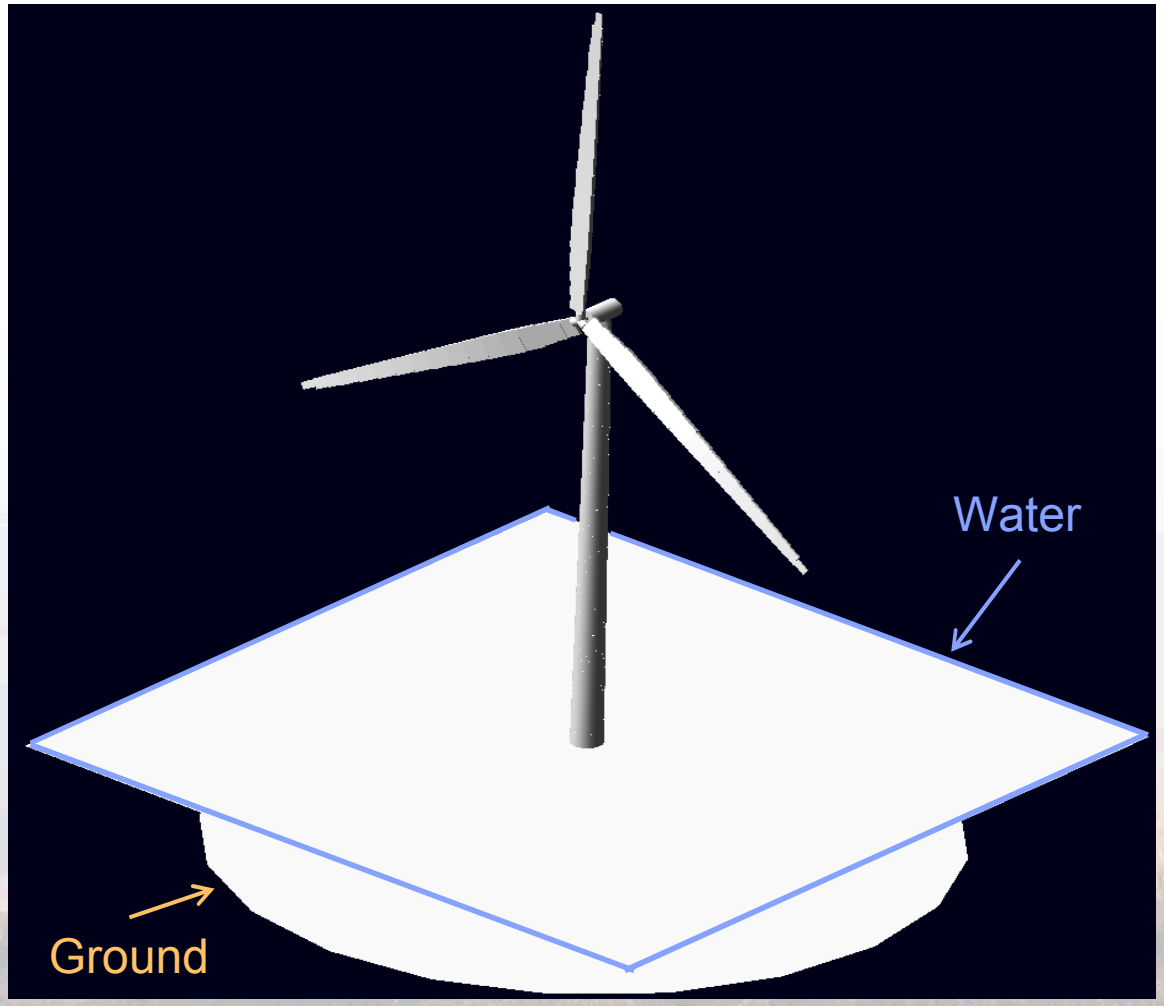


Full Turbine Simulations

- Reduced order blade models integrated into 5-MW offshore turbine models in FAST and ADAMS



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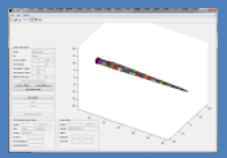

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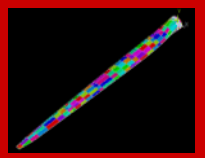

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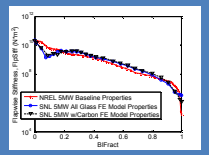

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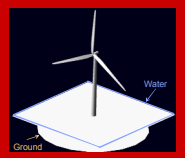

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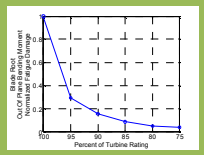

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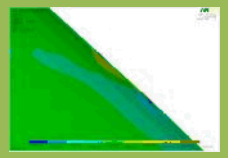

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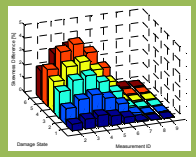

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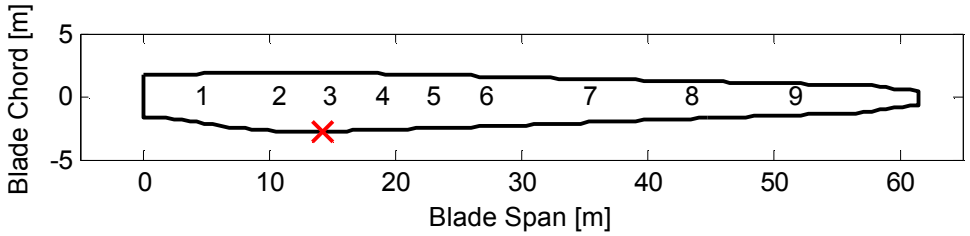
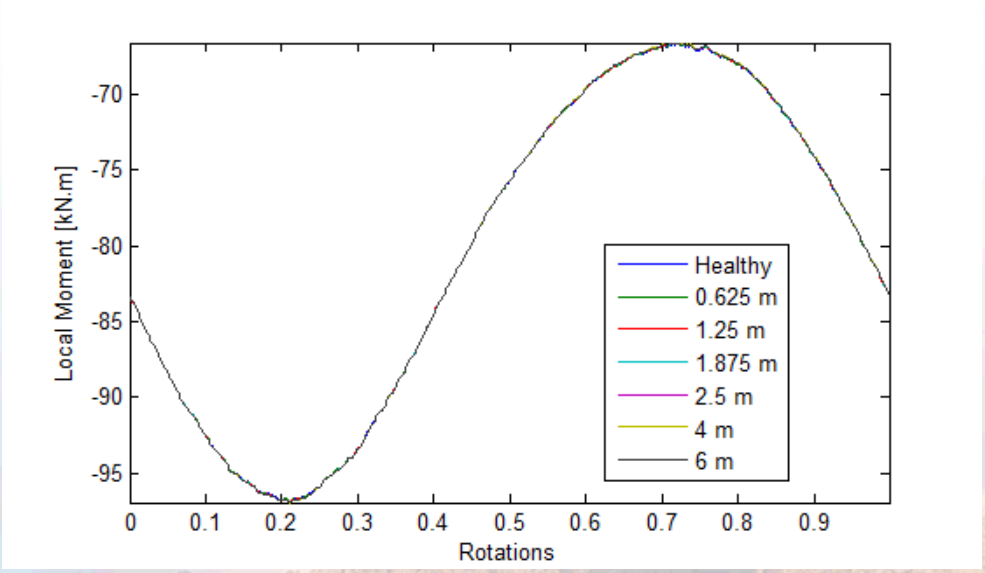
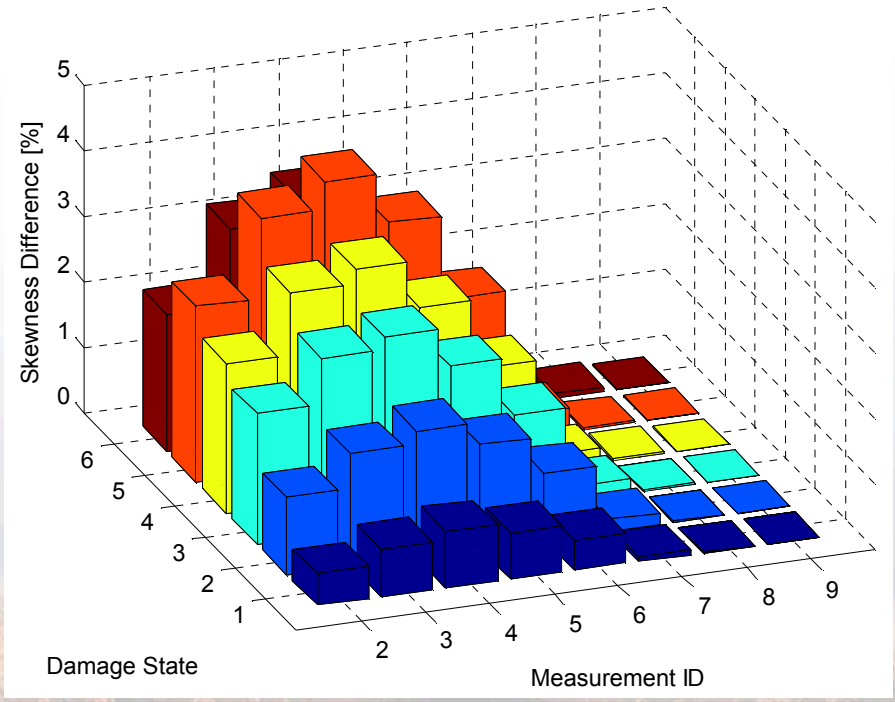
FAST Sensitivity results

- Skewness of pitching moment on damaged blade demonstrated highest sensitivity to presence and size of disbond

$$\hat{\tau} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{3/2}}$$

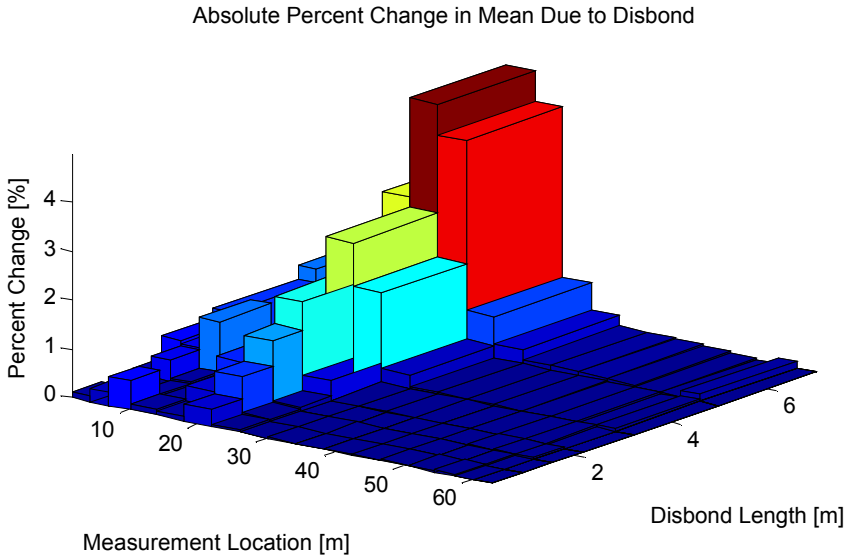


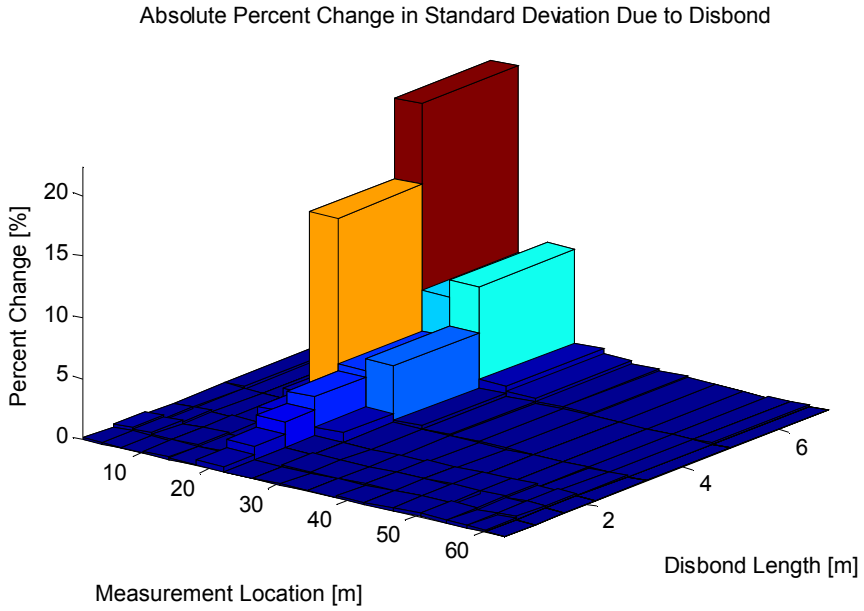


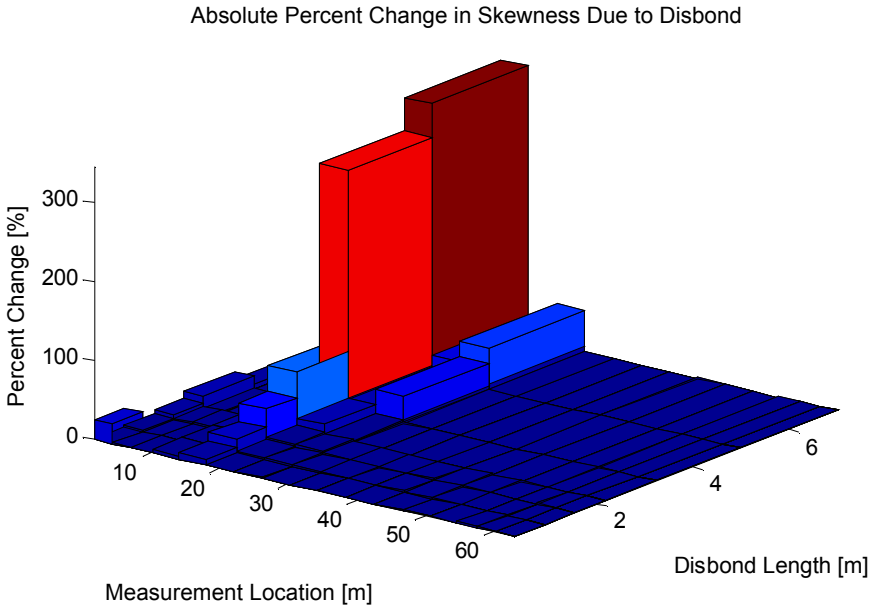


Full Offshore Turbine Simulations using ADAMS

- 1,007 total response measurements both on- and off-rotor were investigated
- Pitching moments once again showed large changes in moments





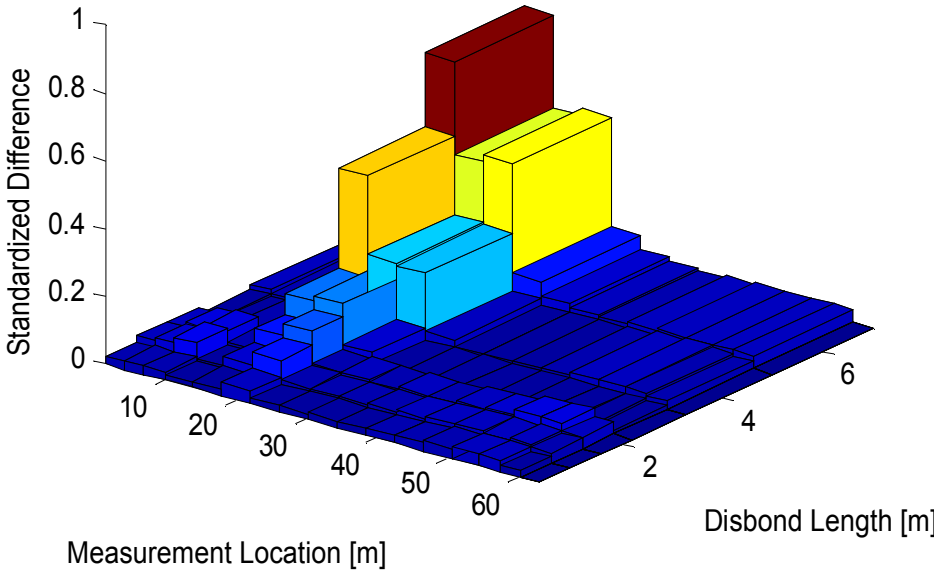


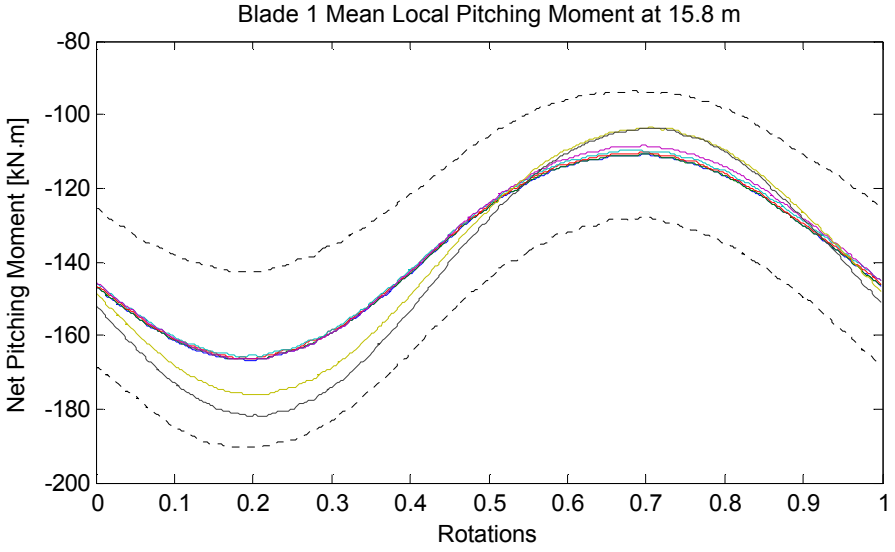
Full Offshore Turbine Simulations using ADAMS

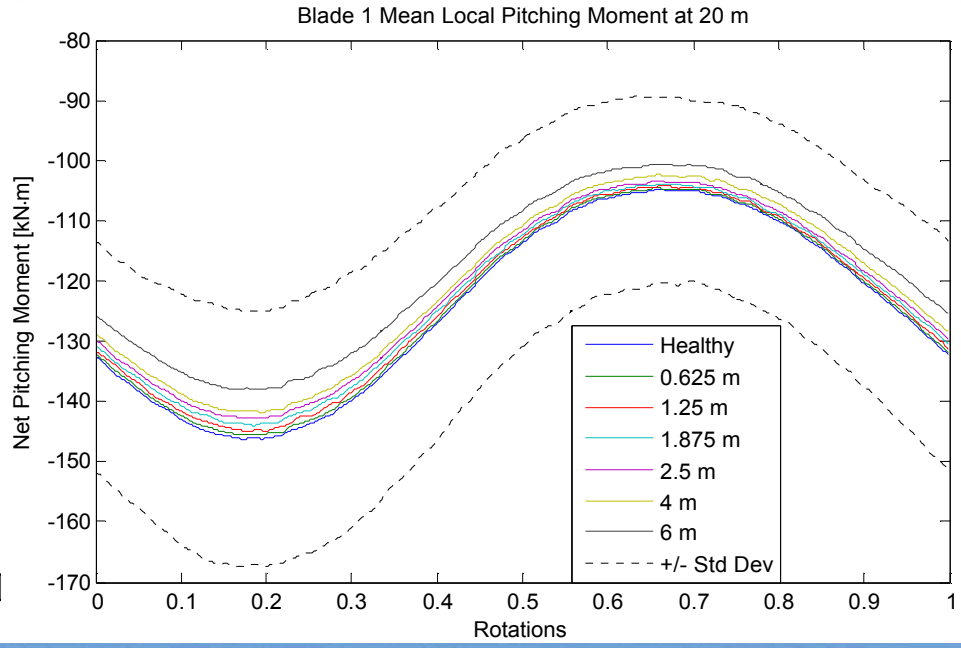
- Average time histories also show significant changes
- Changes localized to damaged region

- Other responses currently being investigated

Max Standardized Difference in Blade 1 Pitching Moments







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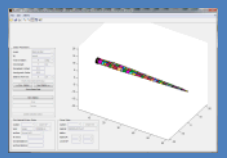

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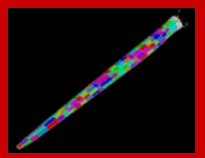

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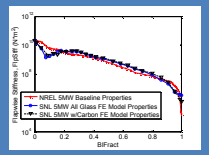

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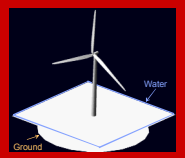

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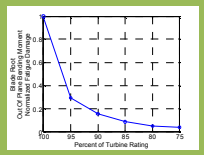

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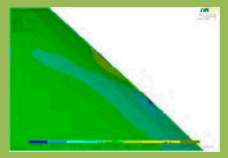

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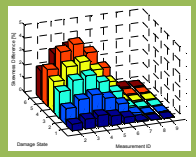

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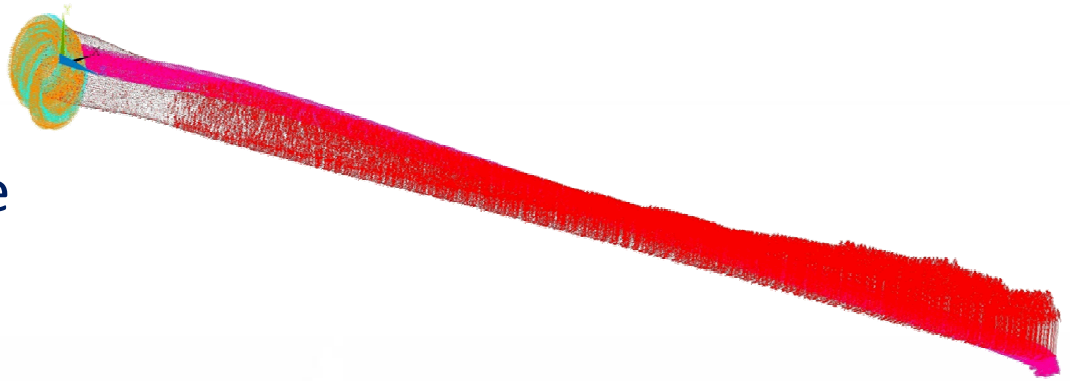
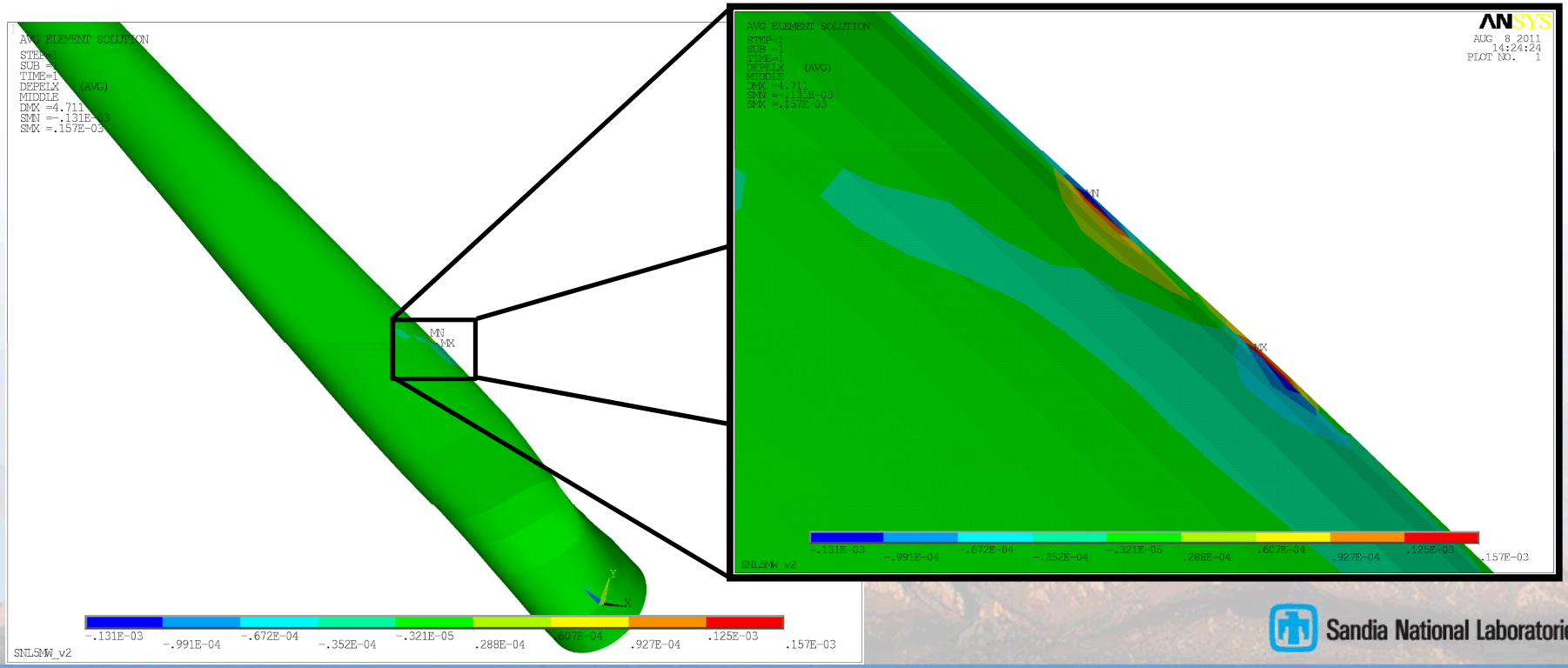
ANSYS Strain Field Investigation

- Disbond results in localized difference in strain localized around the edges of the disbond

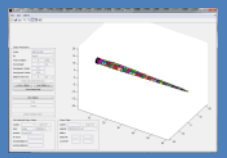




Approach: Simulation Methodology

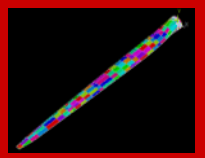
Healthy / Damaged Blade Model

(ANSYS)



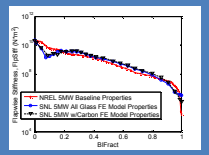
High Fidelity Simulations

(ANSYS)



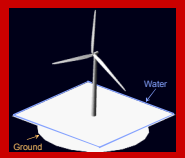
Equivalent Blade Model

(SNL BPE)



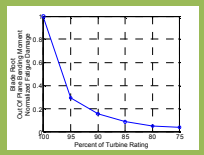
Full Turbine Simulations

(NREL FAST)



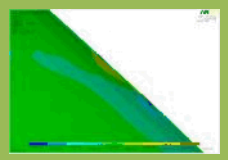
Damage Mitigating Control

(FAST)



Local Sensitivity

(ANSYS)

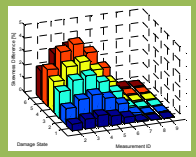


Offshore Turbine Model

(NREL 5MW)

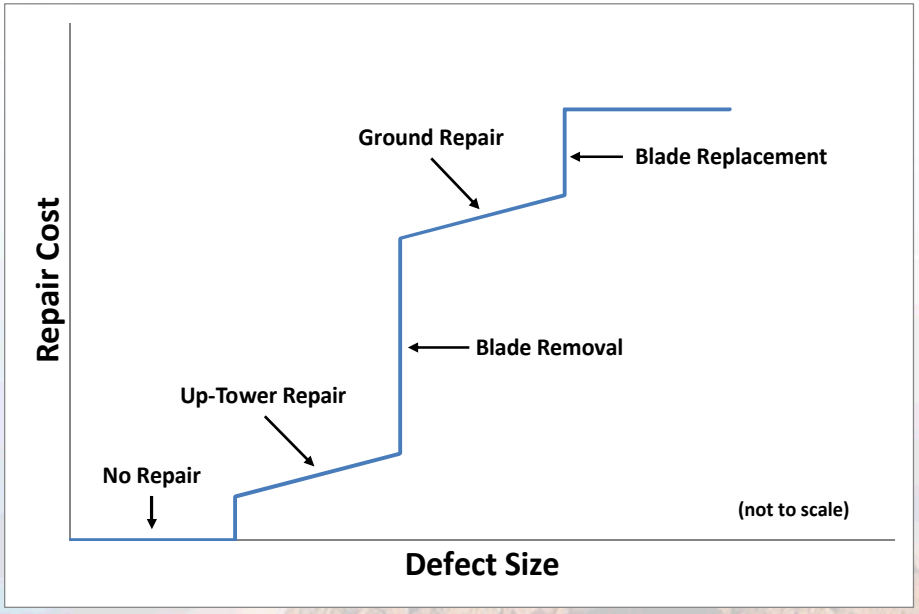
Global Operating Sensitivity

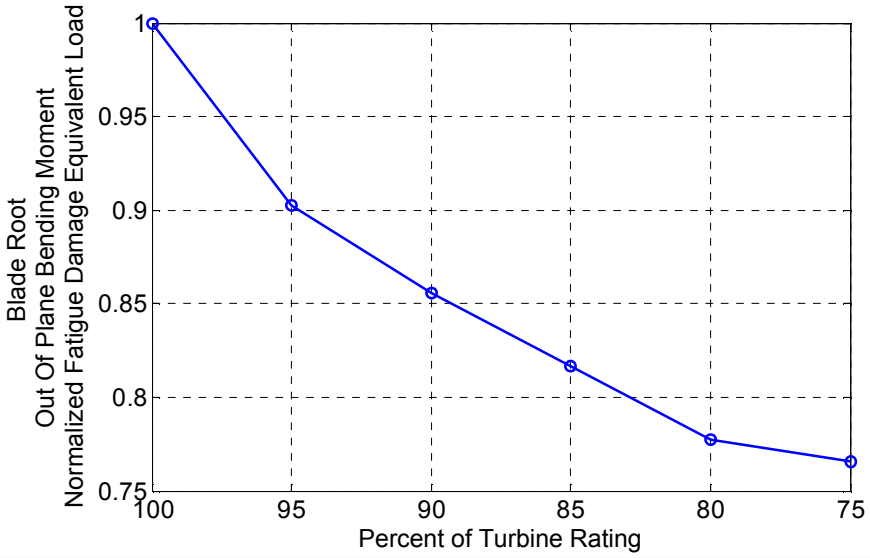
(ANSYS)

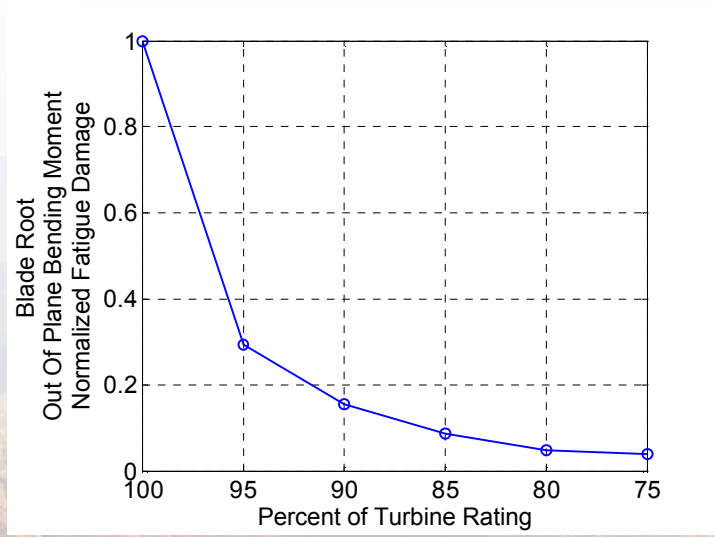


Use of SHPM for Smart Turbine Load Management

- Smart load management can be used to extend blade life for O&M purposes



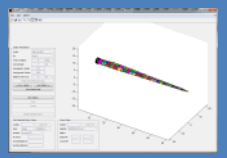




Approach: Simulation Methodology

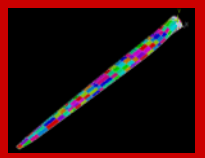
Healthy / Damaged Blade Model

(ANSYS)



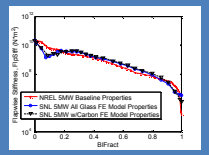
High Fidelity Simulations

(ANSYS)



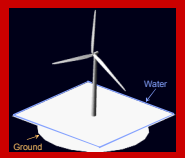
Equivalent Blade Model

(SNL BPE)



Full Turbine Simulations

(NREL FAST)



Damage Mitigating Control

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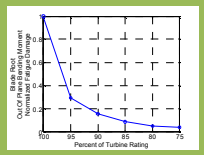
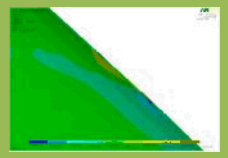


Local Sensitivity

(ANSYS)

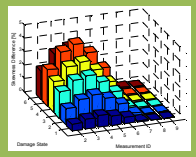


Offshore Turbine Model

(NREL 5MW)

Global Operating Sensitivity

(ANSYS)



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Conclusions

- A multiscale methodology has been developed to investigate the sensitivity of operational response measurements to a representative form of damage
- The effect of trailing edge disbonds on the operation of a offshore turbine was simulated and the most sensitive measurements moments and strains around damage

Future Work

- Extend cost modeling and smart load management methodology
- Extend developed simulation methodology to alternative forms of damage
- Perform small-scale experimental verification of at least one damage model

References

1. W. Musial, R. Thresher, B. Ram. *Large-Scale Offshore Wind Energy for the United States: Assessment of Opportunities and Barriers.* CO, Golden: National Renewable Energy Laboratory, 2010.
2. http://www.eurocopter.co.uk
3. http://www.oceanpowermagazine.net
4. http://www.netcomposites.com
5. Kooijman, H.J.T., Lindenburg, C., Winkelaar, D., and van der Hooft, E.L., “DOWEC 6 MW Pre-Design: Aero-elastic modeling of the DOWEC 6 MW pre-design in PHATAS,” ECN-CX--01-135, DOWEC 10046_009, Petten, the Netherlands: Energy Research Center of the Netherlands, September 2003.
6. Lindenburg, C., “Aeroelastic Modeling of the LMH64-5 Blade,” DOWEC-02-KL-083/0, DOWEC 10083_001, Petten, the Netherlands: Energy Research Center of the Netherlands, December 2002.
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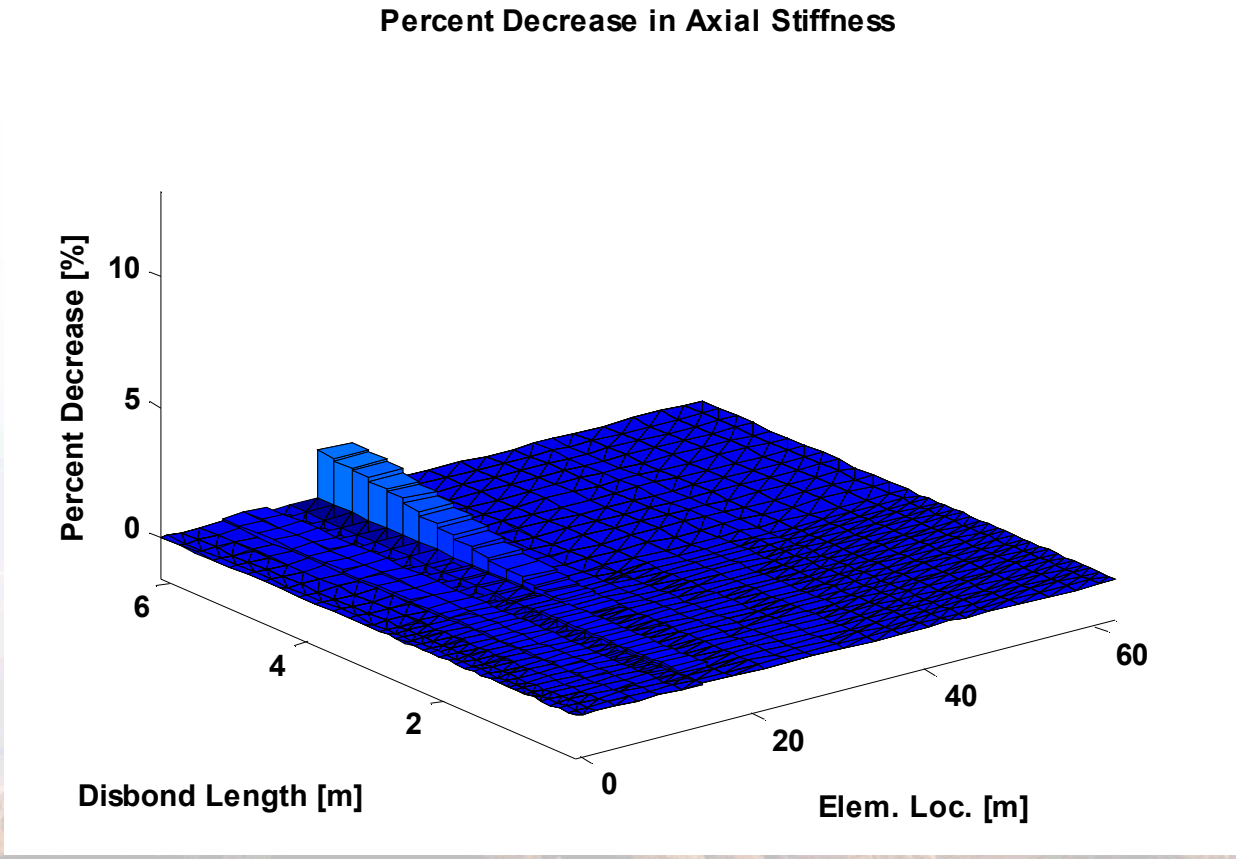
Stiffness Changes due to Trailing Edge Disbonds

- Axial stiffness decreased by less than 2% over range of investigated disbonds
  - Almost no decreases in stiffness value seen for disbond lengths of less than 1 meter



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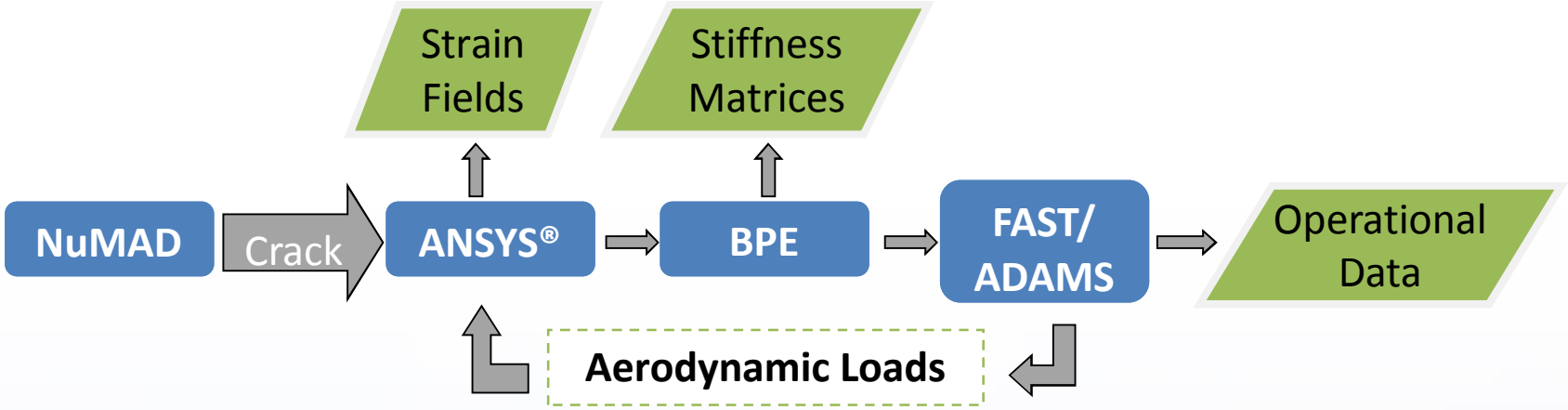
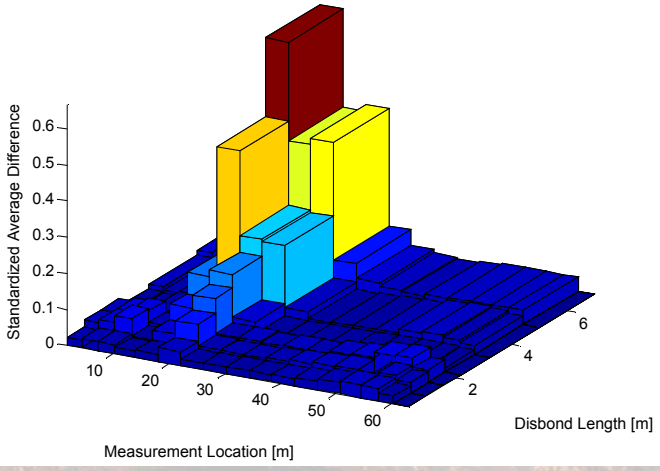


- The effect of trailing edge disbonds on the operation of a offshore turbine was simulated
  - Variations in the blade's strain field were localized around the disbond
  - The net pitching moments on the blade near the disbond were the most sensitive operational measurements



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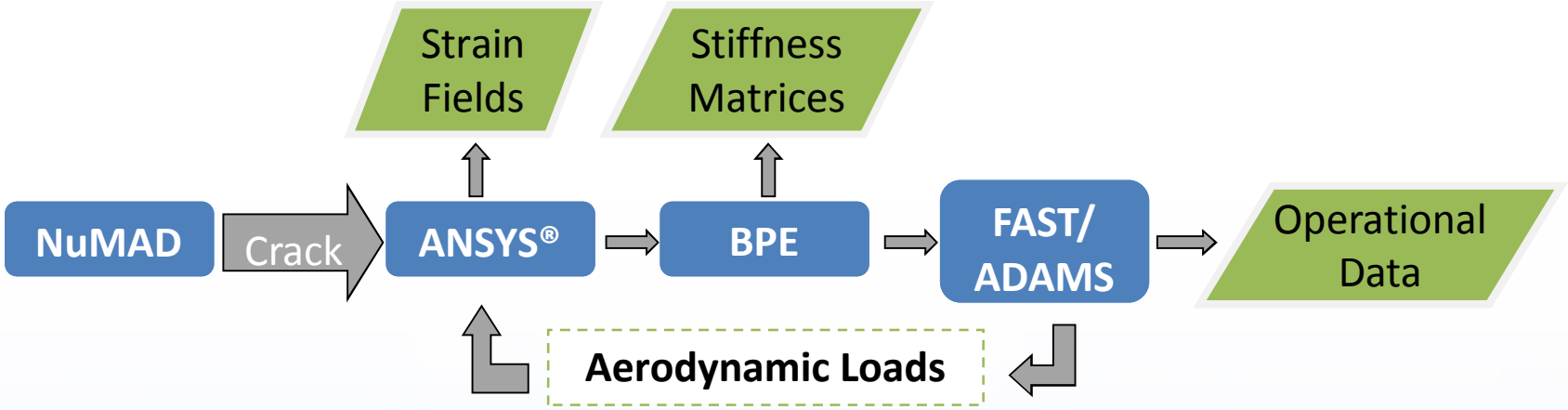

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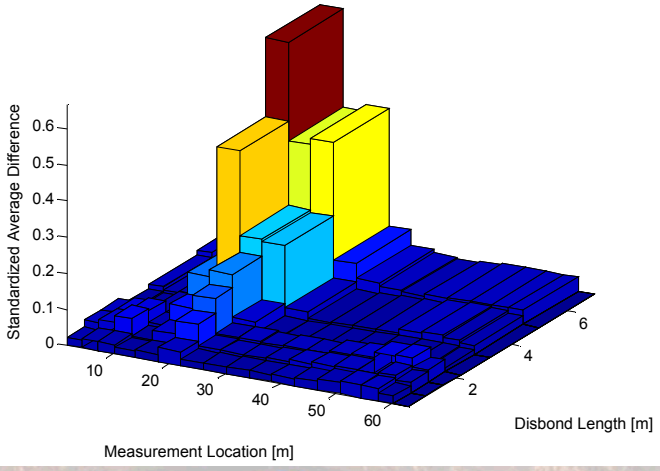

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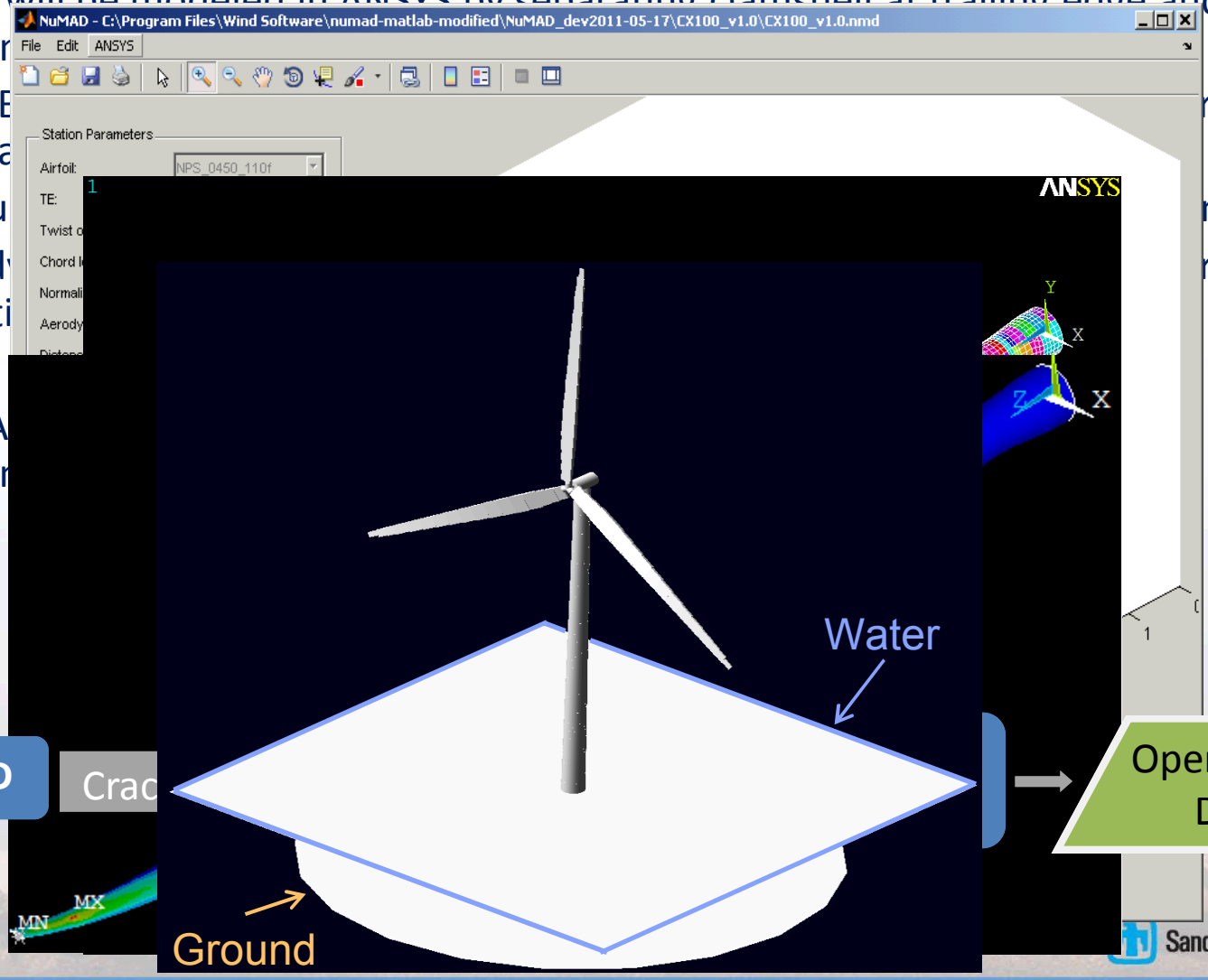
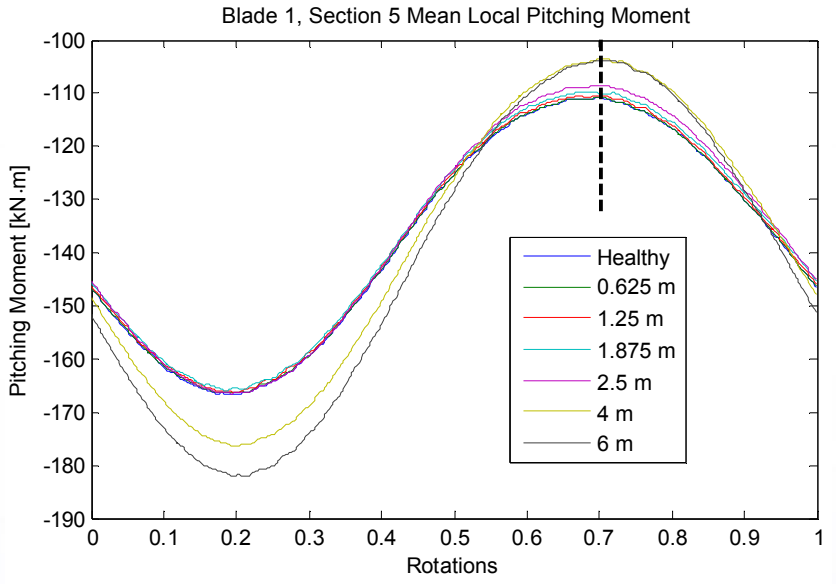
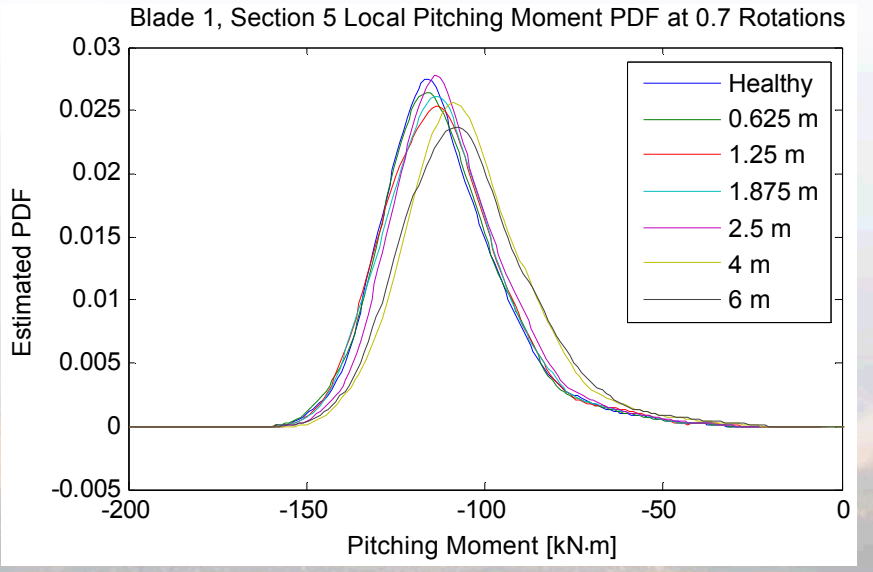


Full Offshore Turbine Simulations using ADAMS

- Estimated PDF of data at a given rotation angle shows change in mean and standard deviation of the data
- Acceleration measurements did not give consistent results for increasing disbond sizes
- In this analysis no off-turbine measurements showed significant sensitivity to the presence of the trailing edge disbond
- Future investigation will include other types of damage which may have a larger impact on the structural response





References

1. W. Musial, R. Thresher, B. Ram. *Large-Scale Offshore Wind Energy for the United States: Assessment of Opportunities and Barriers.* CO, Golden: National Renewable Energy Laboratory, 2010.
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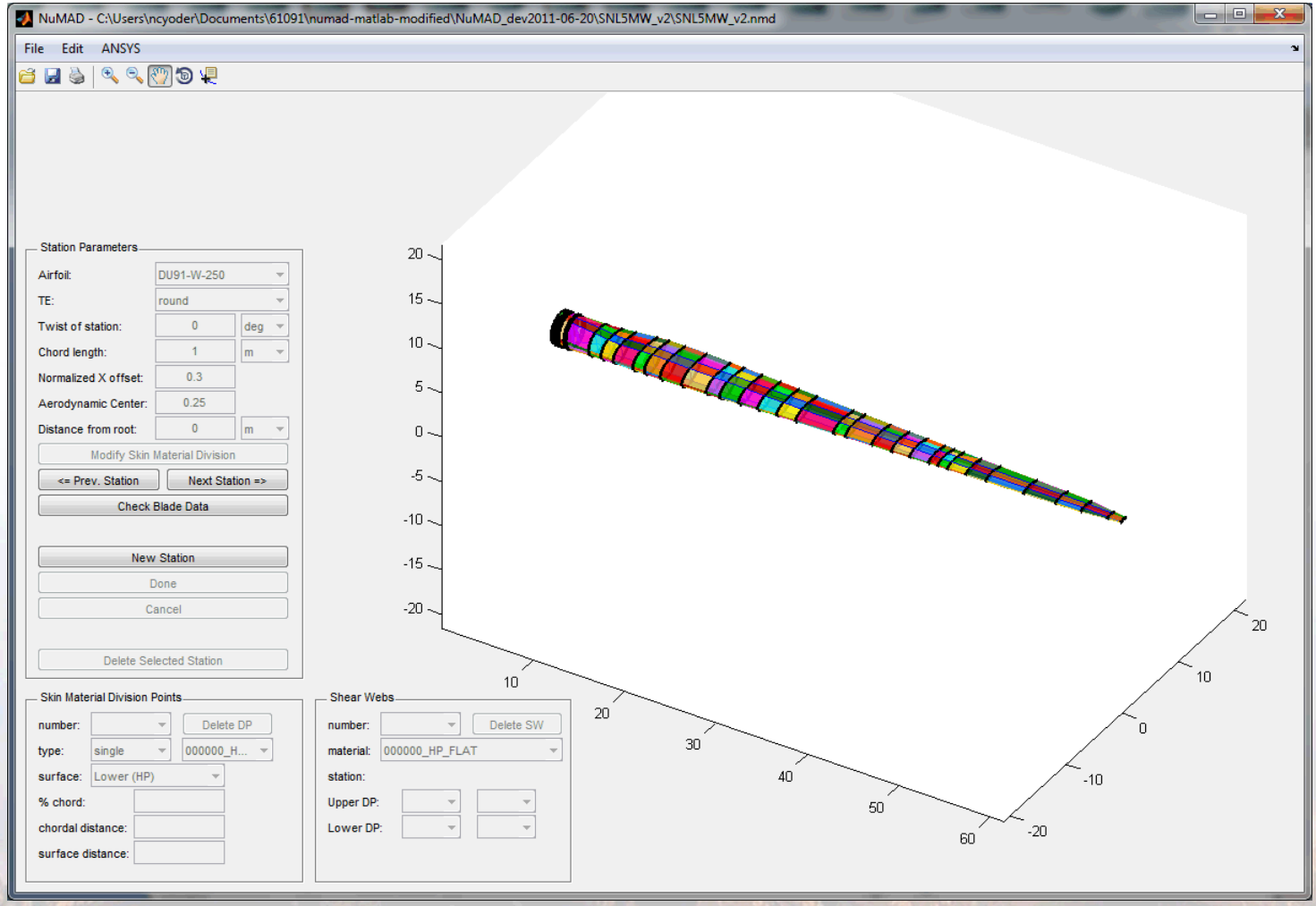

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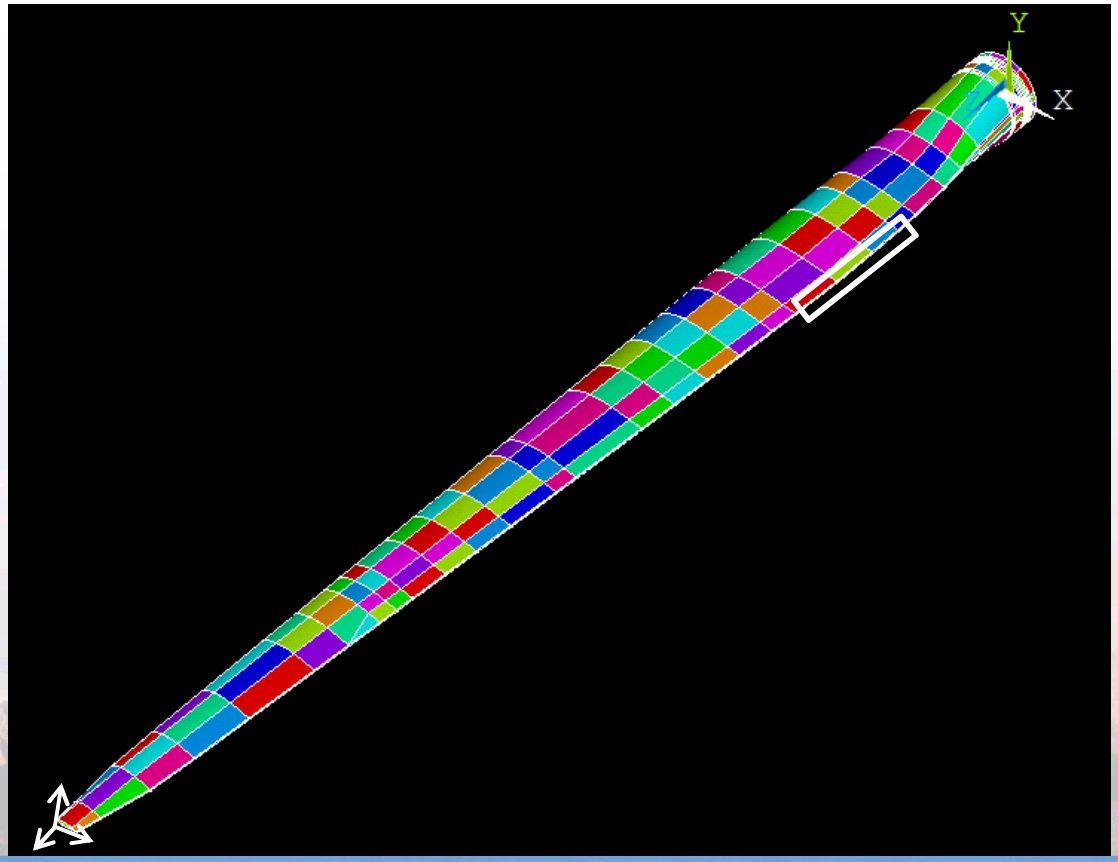

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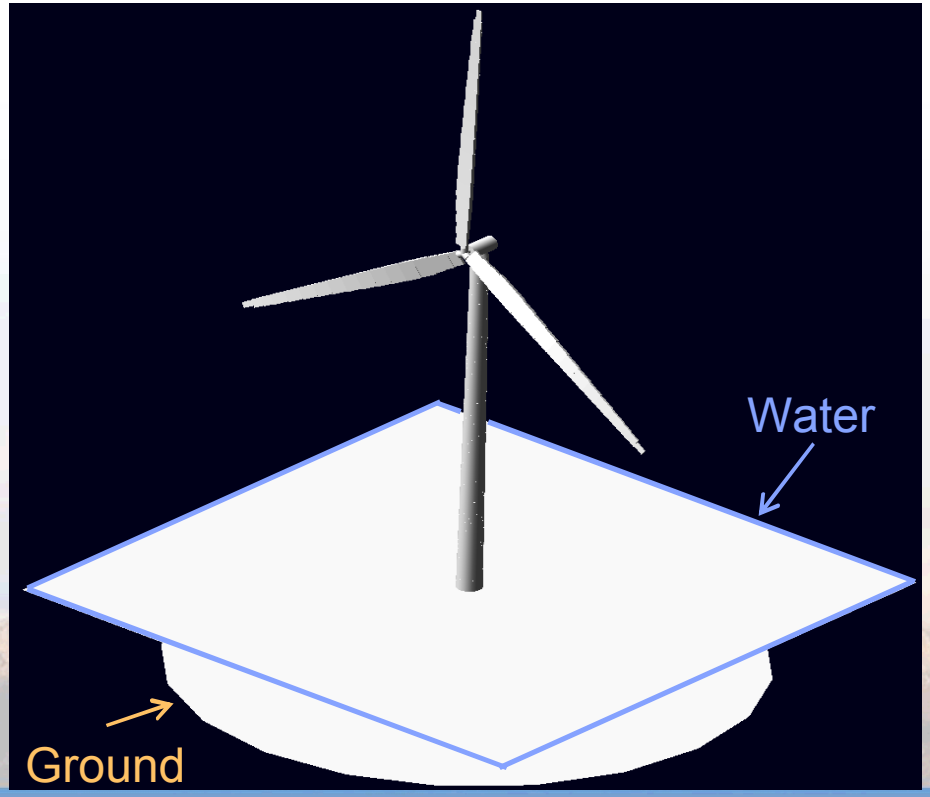

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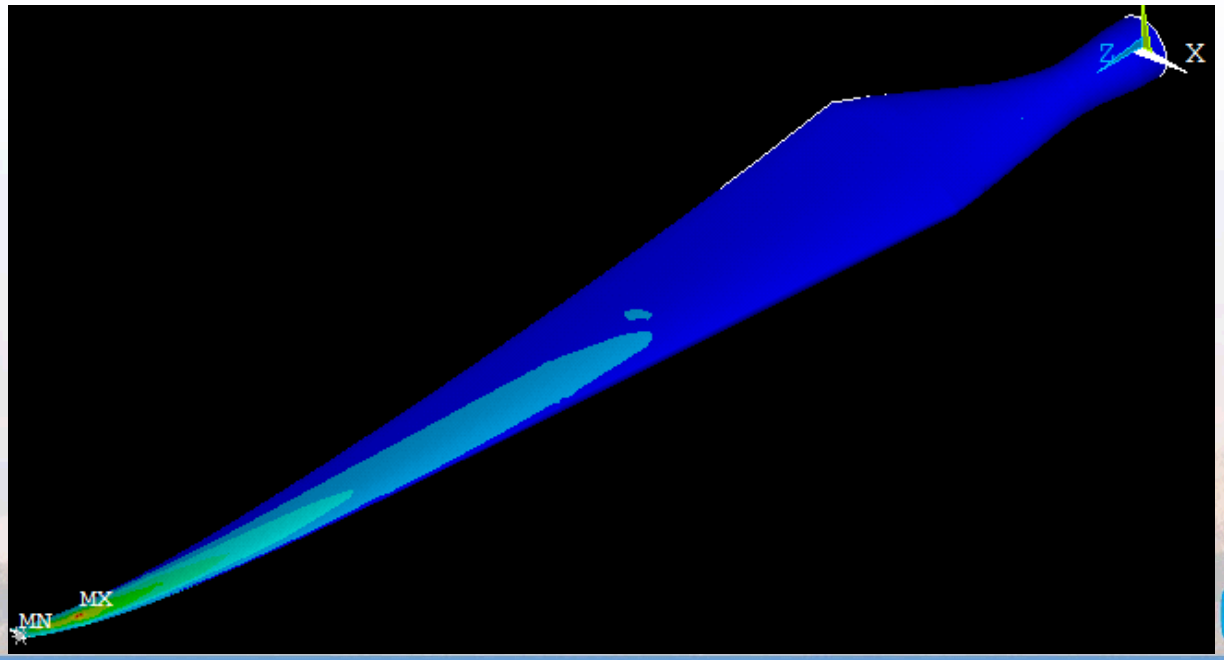

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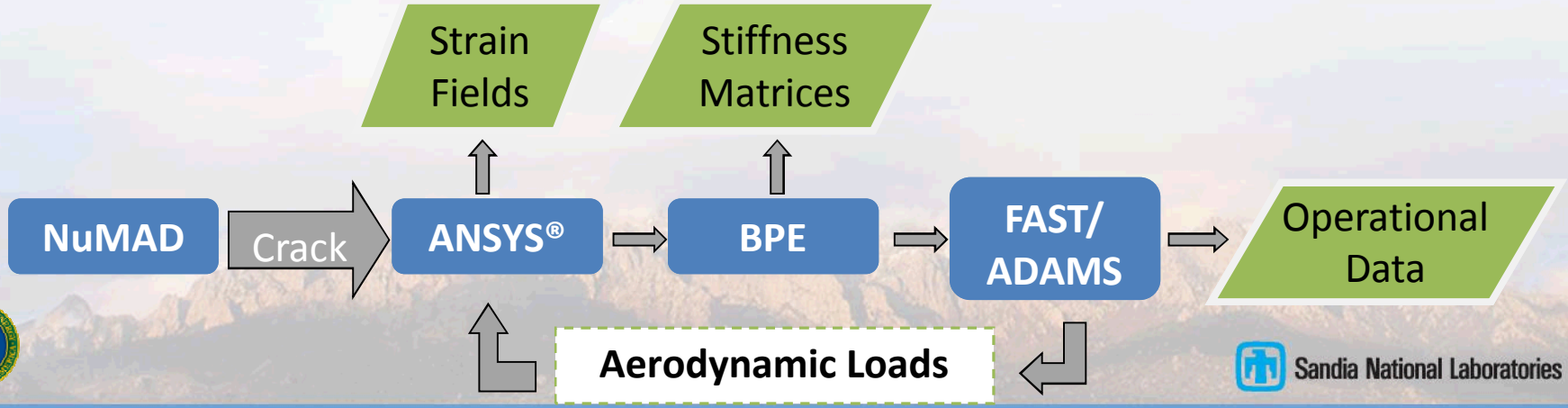
RESULT: A physics based identification of operational response measurements that are sensitive to the presence and extent of a trailing edge disbond.

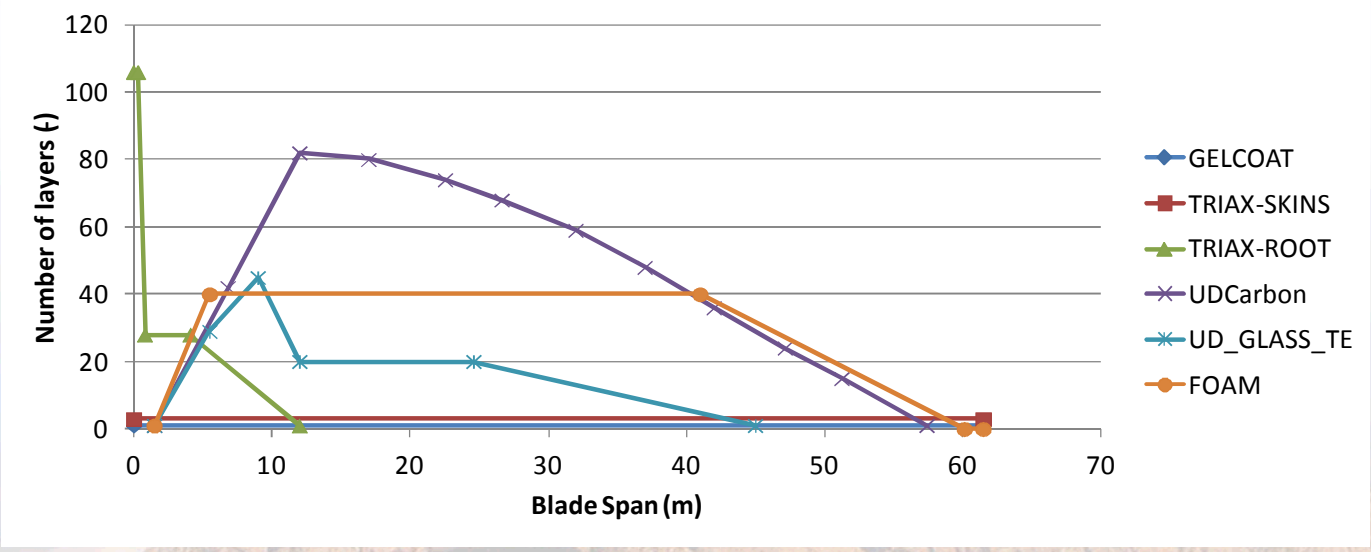


SNL 5-MW NuMAD Blade Model

- A NuMAD blade model of a 61.5 m blade was created using existing blade geometry from the DOWEC[5,6] study for the preliminary model development

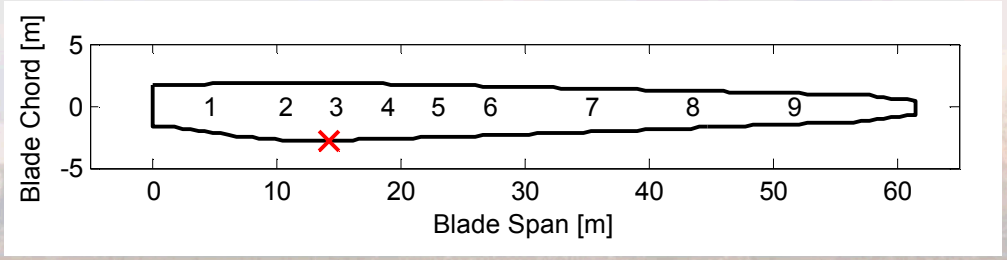
- First model was heavier than NREL 5-MW reference wind turbine[7] so UD carbon spar caps were added

Model Version	Total Mass
Specified weight of NREL 5MW Blade	17,740 kg
Fiberglass Blade Model Weight	25,630 kg
Weight of Blade Model With Carbon Spar Caps	16,381 kg



Full Offshore Turbine Simulations using FAST

- To investigate the effects of a trailing edge disbond on the full turbine response seven different turbine models were created
  - One model had three healthy blades with identical stiffness parameters
  - Damaged models had a single blade with a 0.625, 1.25, 1.875, 2.5, 4 or 6 meter long disbond extending from max chord
- NREL's 5-MW offshore reference turbine model with a fixed monopile in 20 meters of water was used for all of the simulations
- Because the goal was the identification of the measurements that were most sensitive to the trailing edge disbond all other simulations components were kept constant between the models
- 199 response measurements analyzed



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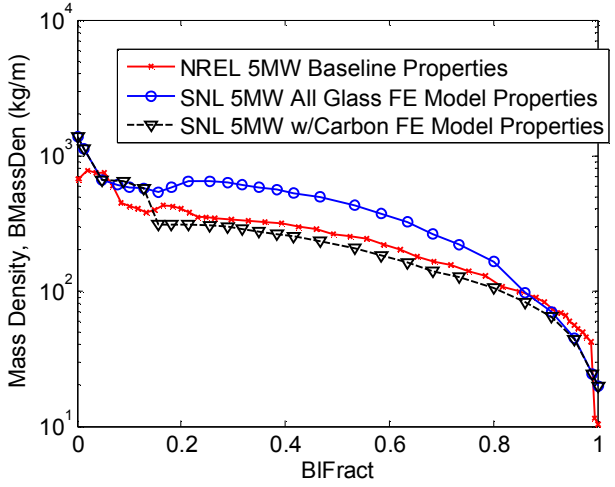
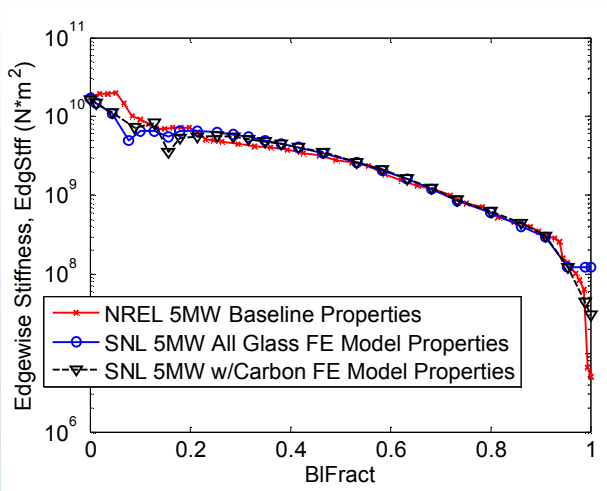
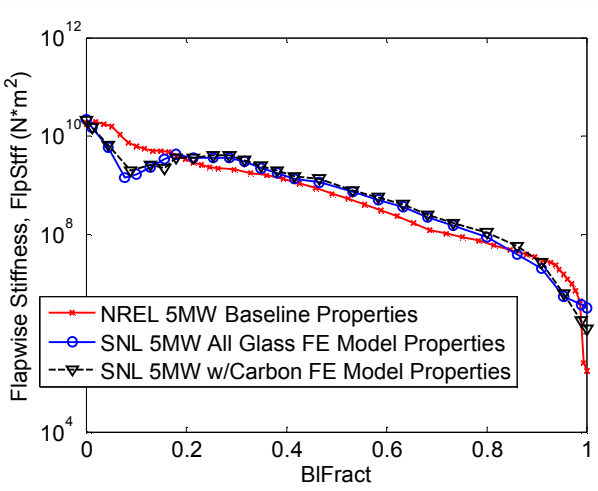
Equivalent Beam Properties with BPE

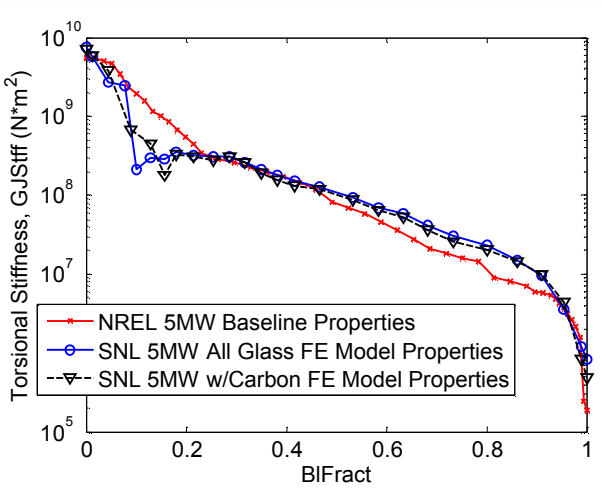
- A Matlab based interface between NuMAD and BPE was created so that equivalent beam properties could be extracted from NuMAD models

- The developed model has effective blade structural properties that closely approximate those used in the NREL 5-MW reference wind turbine blades[7]









Damaged Beam Properties with BPE

- BPE was modified to allow for the automated insertion of variable length disbonds at a user specified location
- Using BPE variety one healthy and a series of damaged blade models were created
  - 36 damaged blades with trailing edge disbonds extending between 0.125 and 6 m outboard from max chord were created
  - BPE modified slightly to improve performance over localized stiffness discontinuities