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Cost Reductions for Offshore Wind Plants through Structural Health and Prognostics Management

D. Todd Griffith, PhD
Sandia National Laboratories

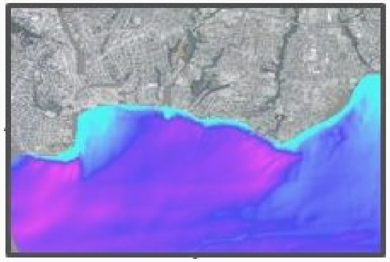
PPHMES 2017 (Invited Talk) -- 2nd Workshop on Probabilistic Prognostics and Health Management of Energy Systems May 15 – 16, 2017 | Lubbock, TX, USA

- **Sandia:** Jon White, Josh Paquette, Brian Resor
- **Purdue / Vanderbilt:** Doug Adams, Noah Myrent, Josh Kusnick, Natalie Barrett, Nasir Bilal
- **ATA Engineering, Inc.:** Nate Yoder, Rory Davis
- **Georgia Tech**: Dewey Hodges, Phillip Richards

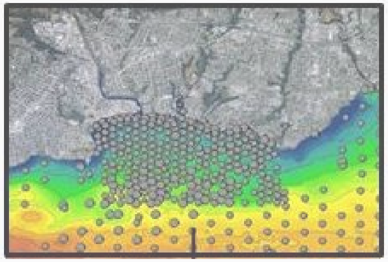
Offshore Wind @ Sandia

- **Vision**: Promote & accelerate the commercial OW industry and **reduce costs** through **technical innovation:**
  - Siting/Permitting: Sediment Transport & Radar
  - Large offshore HAWT rotors
  - Deepwater VAWT system
  - Structural health and prognostics management
  - Offshore wind farm modeling

Waves and Currents



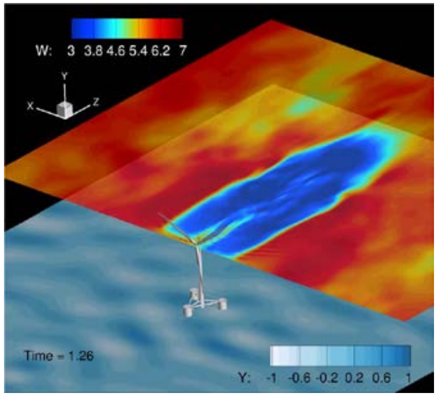
Sediment Characteristics

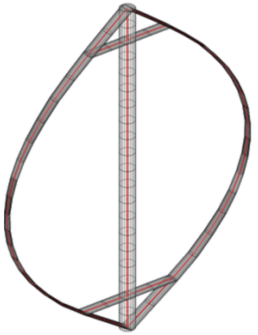


Offshore Siting Analysis

Sensing, Structural Health, and Prognostics

High-resolution Offshore Wind Farm Modeling





Deepwater Offshore VAWT

Large Offshore Rotors

VAWT Flutter – Sandia 2-meter testbed (1980’s)

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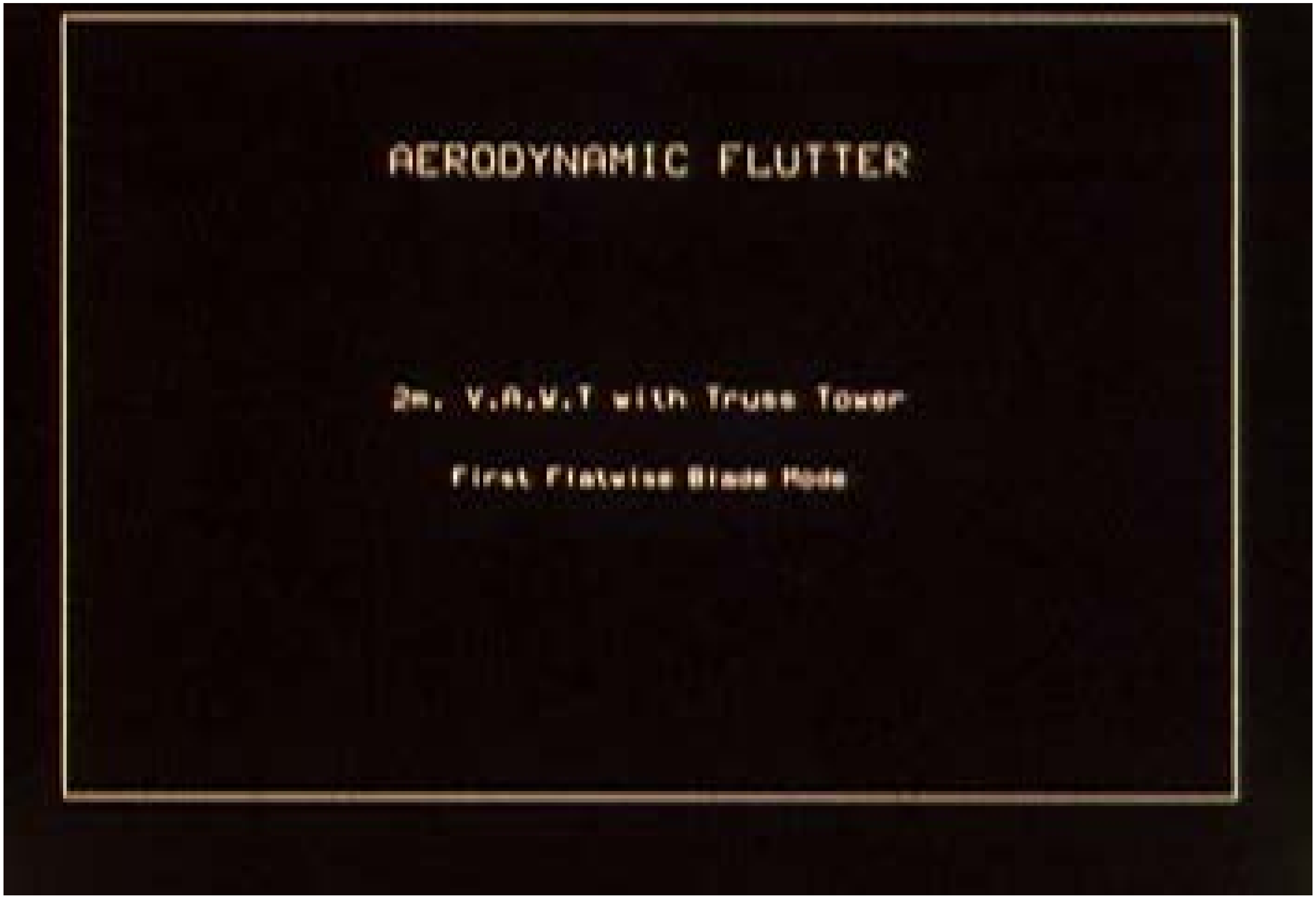
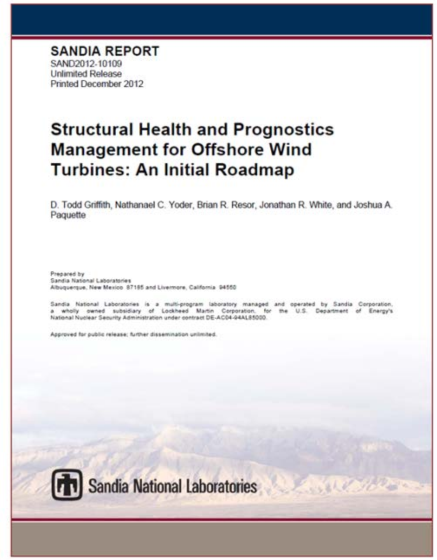


Structural Health and Prognostics Management

- **Summary/LCOE Impact**
  - **Mitigate rising costs for offshore O&M** (estimated to be 2-5 times of land-based)
  - **Maximize energy capture** by increasing availability
- **Focus Areas**

  Simulation of Damage:
  1. Identify best operating signatures (sensors) : Damage Detection
  2. Analyze effects of damage (state of health and remaining life): Prognostics; Damage Mitigation
- **Key Blade Downtime Issues**
  - Rotor imbalance
  - Trailing edge disbonds
  - Leading edge cracks
  - Edge-wise vibration
  - Erosion
  - Lighting
  - Icing



SANDIA REPORT
SAND2012-10109
Unlimited Release
Printed December 2012

Structural Health and Prognostics Management for Offshore Wind Turbines: An Initial Roadmap

D. Todd Griffith, Nathanael C. Yoder, Brian R. Resor, Jonathan R. White, and Joshua A. Paquette

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Initial Roadmap Report

Motivations for a Structural Health and Prognostics Management System

A SHPM system that can be used to:

1. Ensure operations in a desired safe state of health
2. Avoid catastrophic failures through advanced warning
3. Aid in planning of maintenance processes versus more costly unplanned servicing
4. Improve energy capture by avoiding unnecessary shutdown

COE affected in 3 areas

$$COE = \frac{ICC*FCR + LRC}{AEP_{net}} + O\&M$$

COE- Cost of Energy ($/kWh)
ICC- Initial Capital Cost ($)
FCR- Fixed Charge Rate (%/yr)
LRC- Levelized Replacement Cost ($/year)
O&M- Operations and Maintenance Costs($/kWh)
AEP- Annual Energy Production (kWh/yr)

ICC ↑
O&M ↓↓
AEP ↑↑↑

Greater motivation offshore with accessibility issues.
Reduce O&M costs and Maximize Energy Capture

Five Year SHPM Program: Final Report

SANDIA REPORT
SAND2015-2593
Unlimited Release
Printed March 2015

Structural Health and Prognostics Management for Offshore Wind Plants: Final Report of Sandia R&D Activities

D. Todd Griffith

Prepared by
Sandia National Laboratories
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"Structural Health and Prognostics Management for Offshore Wind Plants: Final Report of Sandia R&D Activities,"

Sandia National Laboratories Technical Report,

SAND2015-2593, March 2015

(310 pages).

Project website:
http://energy.sandia.gov/energy/renewable-energy/wind-power/materials-reliability-standards/structural-health-monitoring/

Major Project Findings
(Main Contributions and Areas for Future Work)

1. A Roadmap for SHPM Technology
2. Multi-scale Damage Modeling and Simulation Methodology
3. Damage Detection Strategies for Common Damage Types
4. State of Health of Damaged Turbines Assessment
5. Maturation of Damage Models for Wind Turbine Blade Analysis
6. Smart Loads Management (e.g. Derating, Damage Mitigating Controls)
7. Optimized Maintenance Process Concepts
8. SHPM Economics Calculations
9. Damage Detection Strategies Tested under Realistic & Variable Inflow Conditions
10. A Framework for SHPM Decision-making

[1] A Roadmap for SHPM Technology

A maturation path for technology development and integration
to produce a cost-effective monitoring system.

SHPM Roadmap: Thrust Areas

- Thrust 1: Identify the critical/relevant damage features
- Thrust 2: Model and characterize the damage features
  - *Thrust 2a:* Effects of damage on operational response (Global Sensitivity)
  - *Thrust 2b:* Effects of damage on blade state of health (Local Sensitivity)
- Thrust 3: Economics analysis: Cost modeling for the SHPM process
- Thrust 4: Operations decisions: SHPM prognostic control actions
- Thrust 5: Operations decisions: SHPM maintenance actions

Table 4. SHPM Technical Maturity Roadmap – Version 1.0

(Key: mature/completed, current, near-term future, longer-term future) As of March 2015

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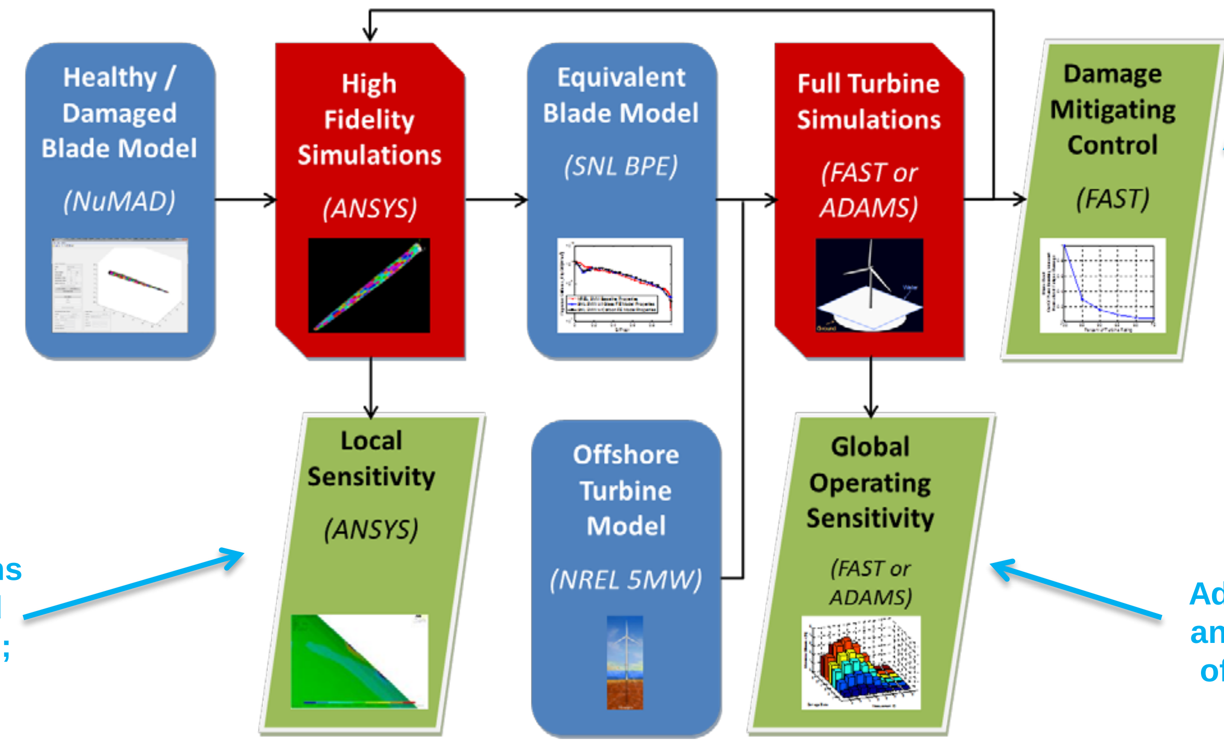
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Thrust Area 1	Identify Relevant Damage Features	• Identify single damage feature #1 • Define criterion for selection: rank based on impact on revenue	• Identify additional important rotor damage features	• Quantify and validate collective effects of these features on revenue loss	• Implement approach for experimental simulation of damage	• Identify and demonstrate the method for non-blade components (e.g. tower)
Thrust Area 2(a)	Model and Characterize Damage Features: *Global Operating Sensitivity*	• Develop methodology to model and simulate damage globally • Identify sensor needs for blade and non-blade sensing for feature #1 • Identify detection strategy for feature #1	• ID sensor needs for multiple features (blade and non-blade) • ID detection strategies for additional features (blade and non-blade) • Comprehensive survey of industry sensor products (turbine and general)	• Mature detection robustness to uncertainties and multiple simultaneous damage features • Mature the damage model (linear versus nonlinear models) of operating sensitivity	• Mature the damage model (progressive damage model) for operating sensitivity • Laboratory demonstration of detection strategies	• Demonstrate detection in field tests on utility-scale rotor
Thrust Area 2(b)	Model and Characterize Damage Features: *Local Damage Effects*	• Develop methodology to model and simulate damage locally • Develop a plan to quantify the blade state of health • Perform targeted load case analysis	• Perform complete set of load case analyses to quantify damage effects on state of health tied to IEC/GL blade design standards	• Mature the damage modeling (linear versus nonlinear models) for buckling and strain calculations	• Mature the damage model (progressive damage model) for effect on local sensitivity	• Demonstrate localized damage effects and their progression in full-scale blade test
Thrust Area 3	SHPM Economics Analysis	• Initial cost model defined for SHPM system assessment (ID inputs/outputs)	• Refine the fidelity of the SHPM cost model • Perform input/output sensitivity studies	• Integrate with simulations in Thrust Areas 2(a) and 2(b) in end to end case study of SHPM system cost and performance	• Field demonstration project to validate SHPM system model performance and economics	• Distribute validated SHPM cost and decision tools to industry
Thrust Area 4	SHPM Operations Decisions: Controls	• Define conceptual prognostic (damage mitigating) control modes	• Refined loads management strategy to avoid catastrophic failure/total loss	• Refined loads management strategy to maximize revenue; to mitigate damage growth	• Model and test/validate the impact of upstream turbine(s) wake on downstream SHPM	• Field demo of prognostic control in utility-scale rotor
Thrust Area 5	SHPM Operations Decisions: Maintenance	• Define conceptual maintenance states for blade SHPM • ID the information needed from sensor/SHM system for maintenance decisions	• Refine/expand model to include other information (vessels, weather, etc.) • Refine the blade repair/replacement cost information • Exercise SHPM cost model with new inputs	• Review loads management strategies in the context of optimal maintenance planning	• End to end simulations that demonstrate the effect of SHPM system on maintenance process economics	• Field test validation of SHPM-based maintenance operations for utility-scale wind farm

Technology Integration

Technology Thrust Maturation Path

[2] Multi-scale Damage Modeling and Simulation Methodology



Decisions regarding operating strategy

Addresses questions about severity and impacts of damage; "state of health" assessment

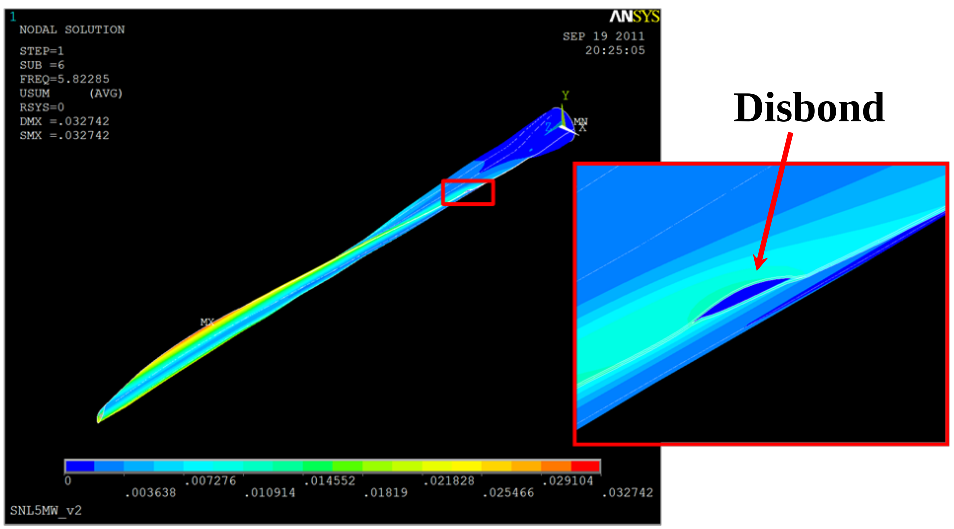
Addresses detection and characterization of damage/faults in operation; "sensing"

Broadly applicable and cost-effective simulation-based methodology for modeling damage

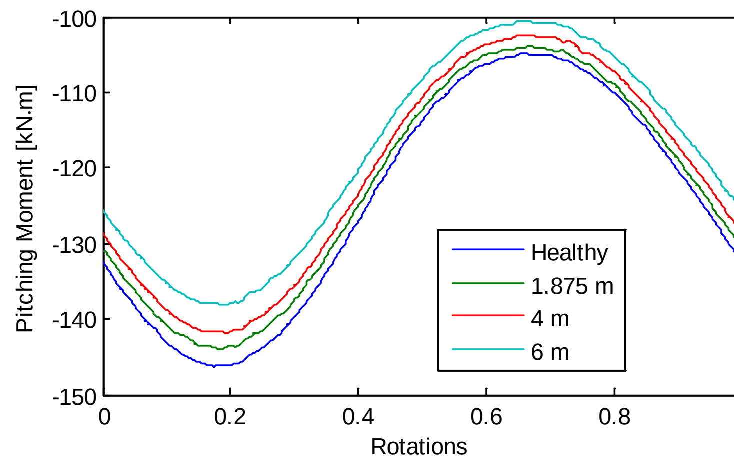
[3] Damage Detection Strategies for Common Damage Types

Example for Trailing Edge Disbond

Also mass and aerodynamic imbalance, shear web disbond.



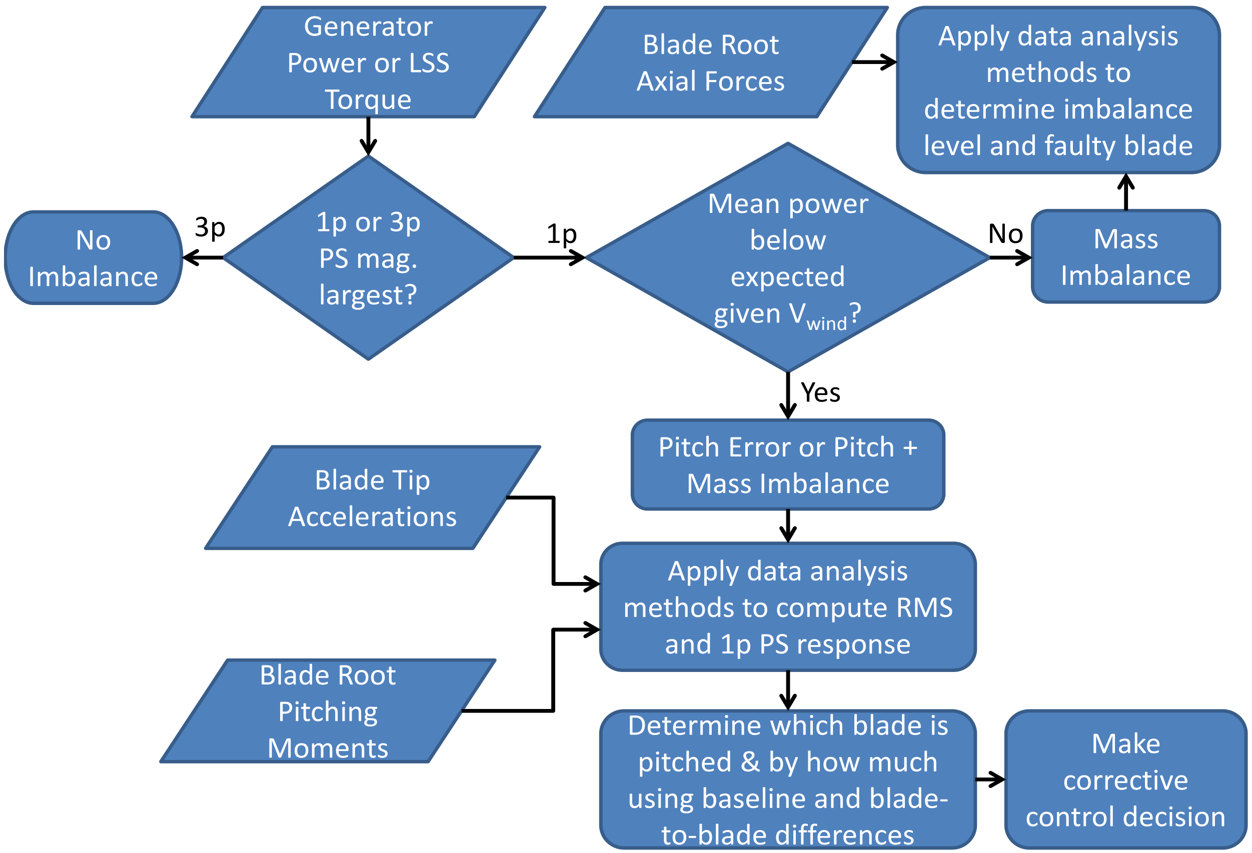
Blade and Non-blade sensing approaches considered for all damage/fault types



Root pitching moment is sensitive to trailing edge disbond

Location and number of sensors affects both cost and performance

Pitch Error and Mass Imbalance Detection Strategy



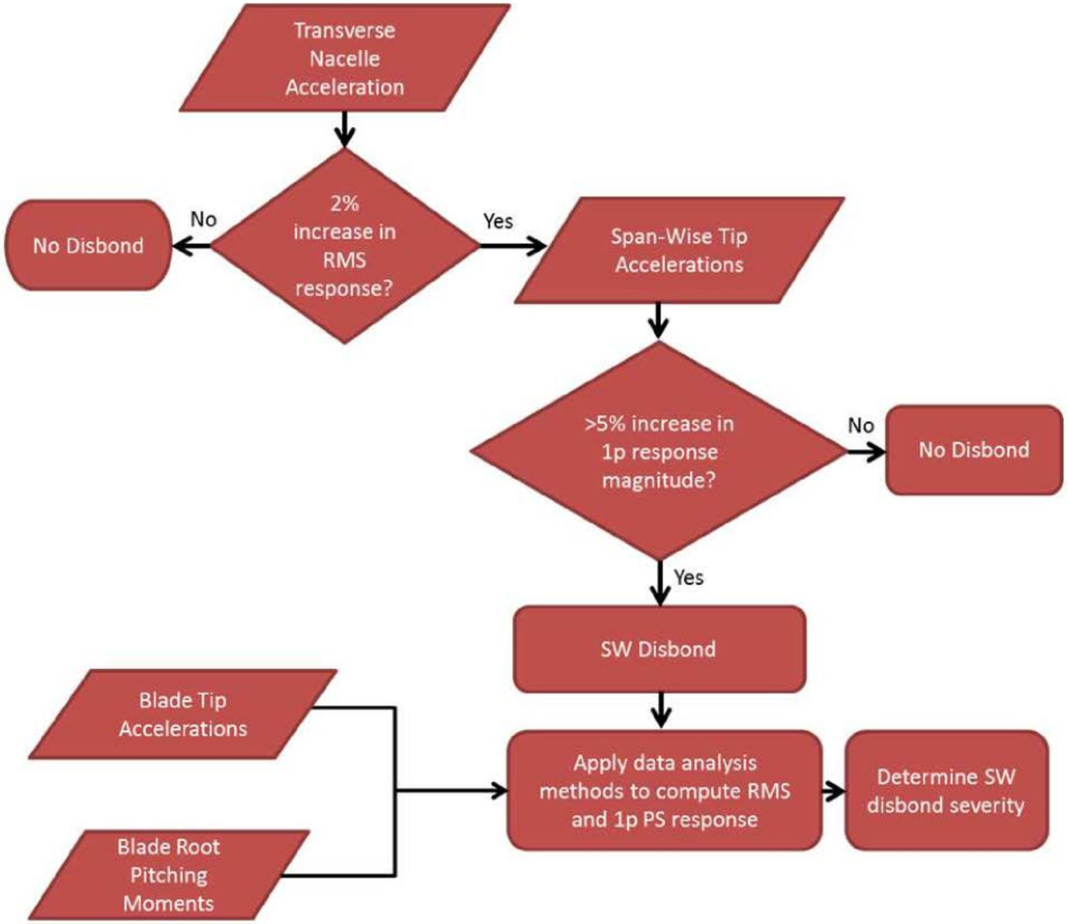
Detection

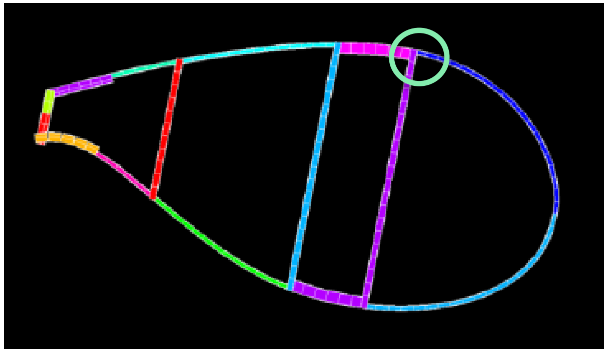
1. Generator Power
2. Blade Root Axial Force

Characterization

1. Blade Tip Acceleration
2. Blade Root Pitching Moment

Refined Shear Web Disbond Detection Strategy





Detection

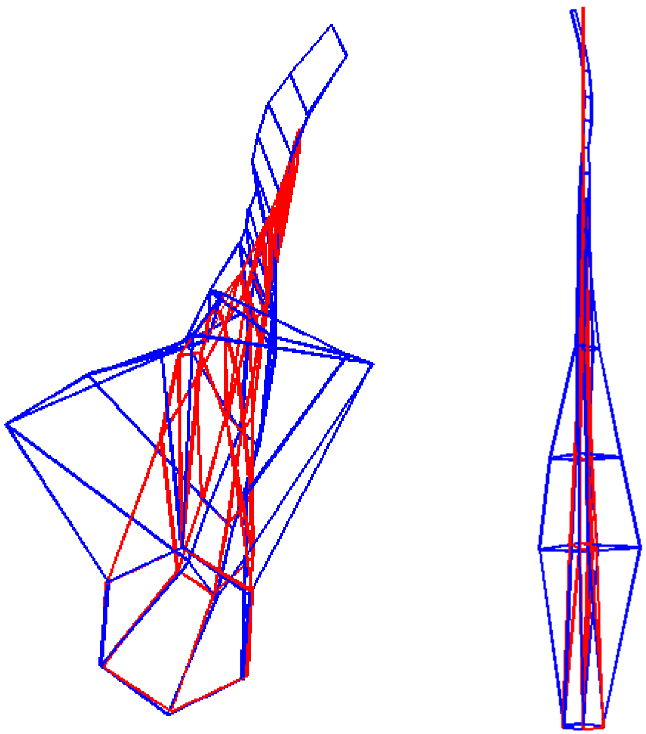
1. Transverse Nacelle Acceleration
2. Span-wise Tip Acceleration

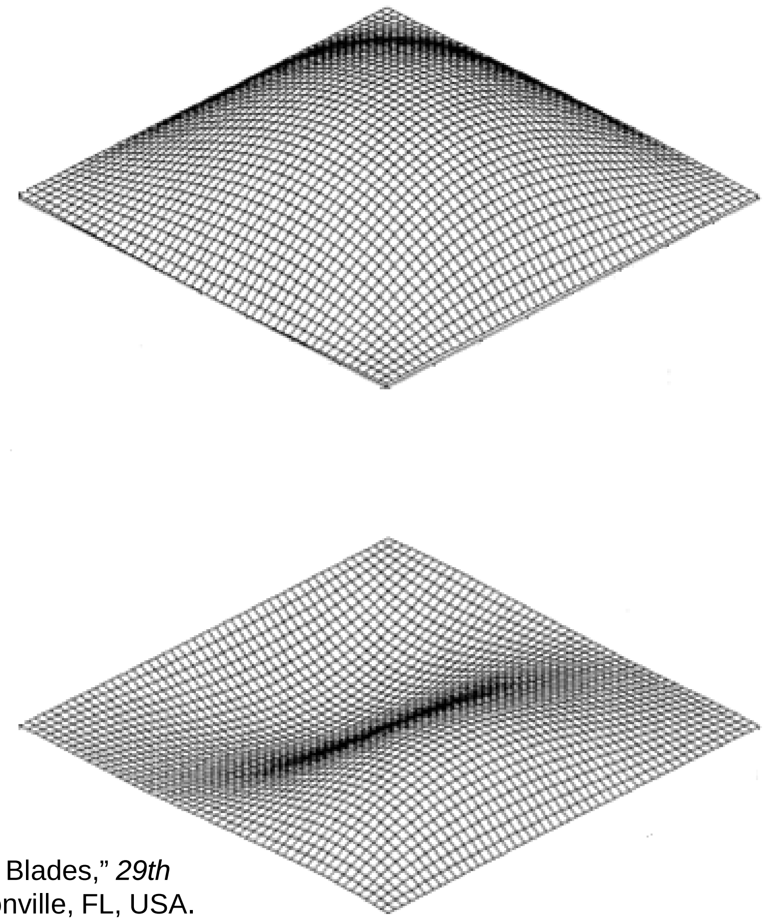
Characterization

1. Blade Tip Acceleration
2. Blade Root Pitching Moment

Panel Modes @ Low Frequency

Mode #4:   22 Hz





Griffith, D.T., “Utilization of Localized Panel Resonant Behavior in Wind Turbine Blades,” *29th International Modal Analysis Conference*, January 31 - February 3, 2011, Jacksonville, FL, USA.

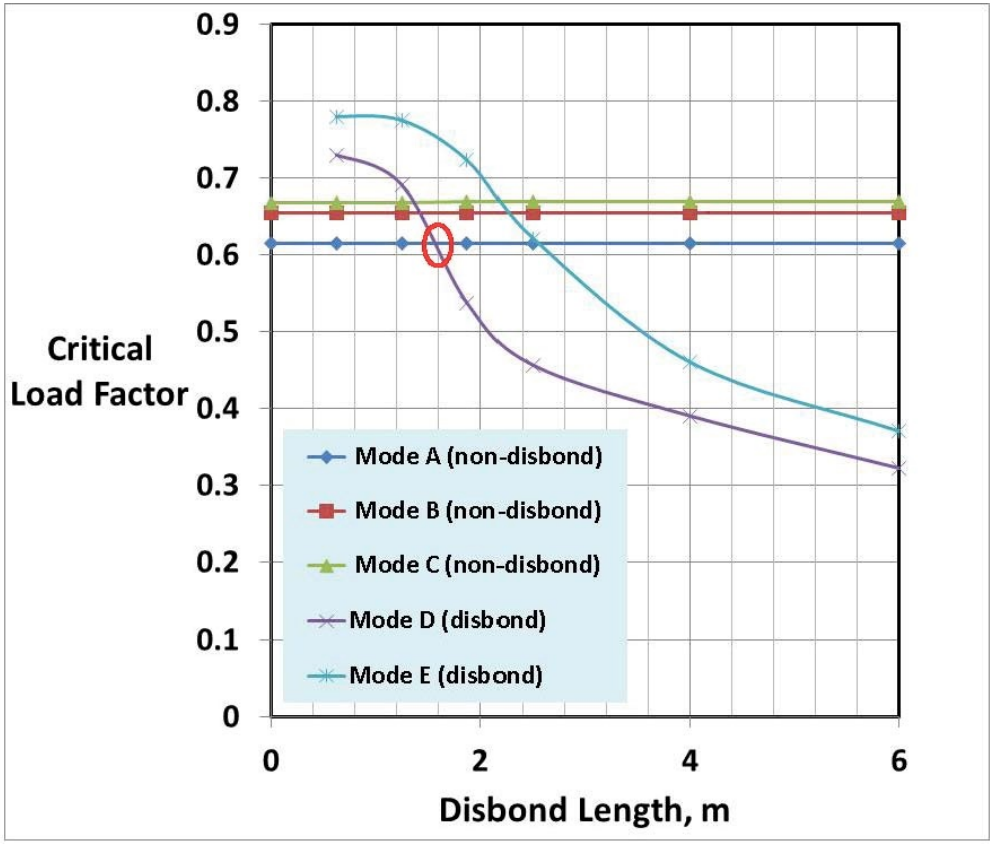
Griffith, D.T. and Paquette, J.A., “Panel Resonant Behavior of Wind Turbine Blades,” *51th AIAA/ SDM Conference*, April 1-4, 2010, Orlando, FL, USA, AIAA-2010-2741.

[4] State of Health Assessment for Damaged Turbines

Design standards-based approach to assess state of health and estimate remaining life.

Design loads analysis of damaged blade performed:

- ✓ Deflection
- ✓ Buckling
- ✓ Fatigue
- ✓ Strain



Critical buckling load factor as a function of disbond size

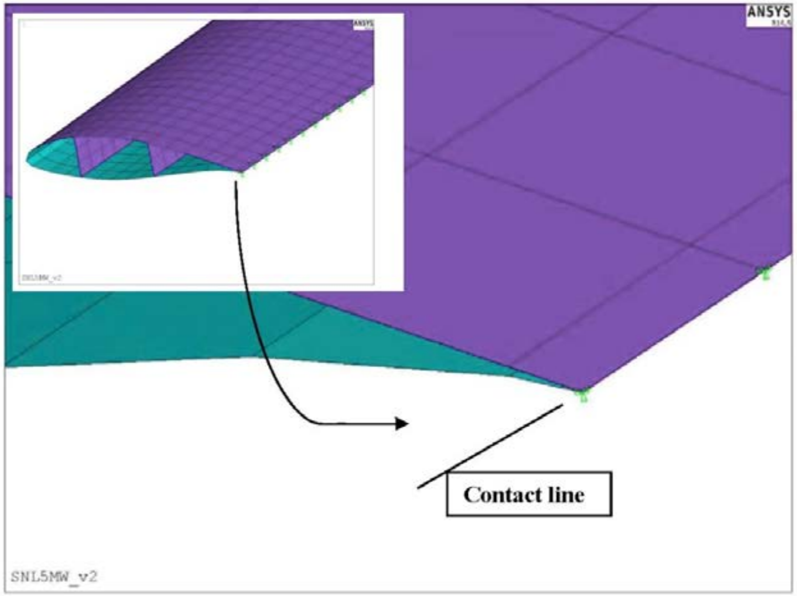
[5] Improved Damage Models for Wind Turbine Blade Analysis

a) Detailed models of blade damage in SNL's NuMAD code

b) From linear to nonlinear models for high-fidelity structural analysis

c) Progressive damage models

d) From linear to nonlinear models for estimating the degraded beam properties of damaged blades



Nonlinear contact elements implemented in SNL/NuMAD blade modeling software.

[6] Smart Loads Management

(e.g. Derating – an illustrative example)

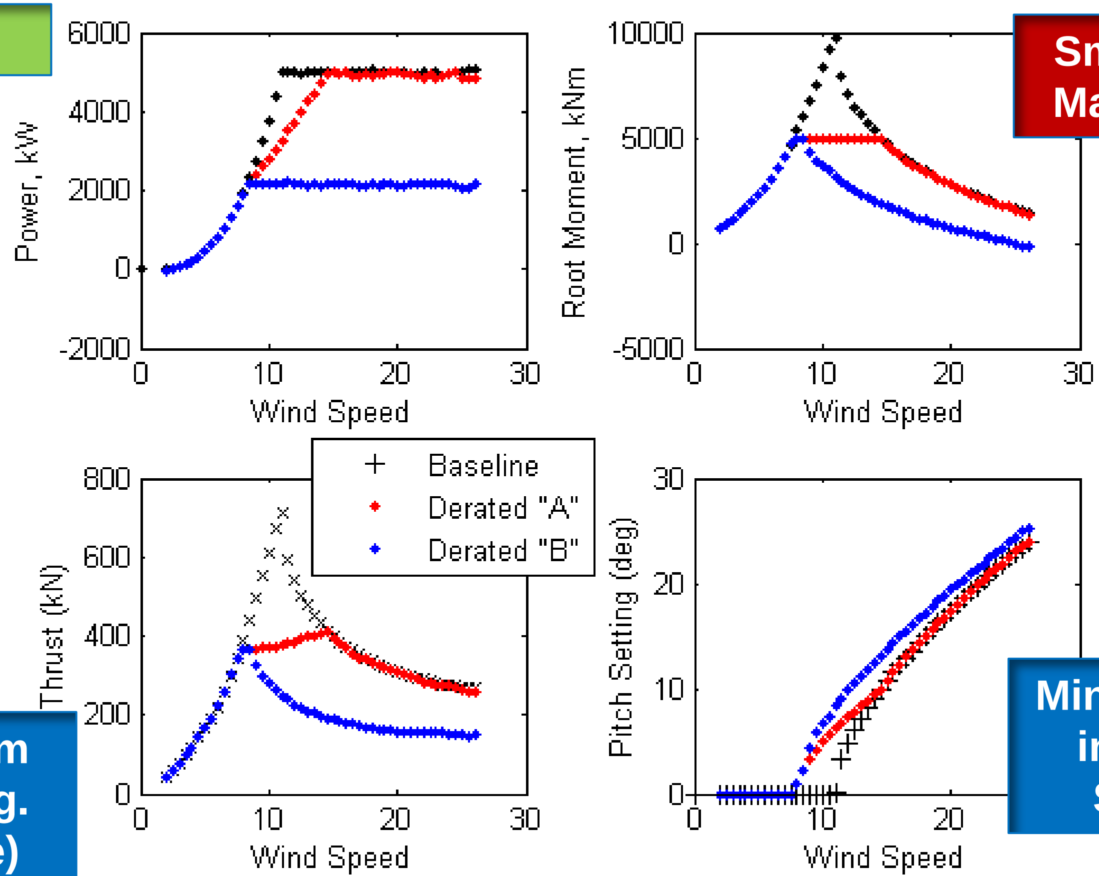
An illustration of 50% loads reduction (i.e. 50% derating) and the impact on revenue.

Revenue

Smart Loads Management

Derated A:
more aggressive

Derated B:
more conservative



Secondary, System Level Benefits (e.g. support structure)

Minor Change in Control Strategy

Increase energy capture and reduce O&M costs with planned maintenance

Smart Loads Management

Effect of Derating on SERRs

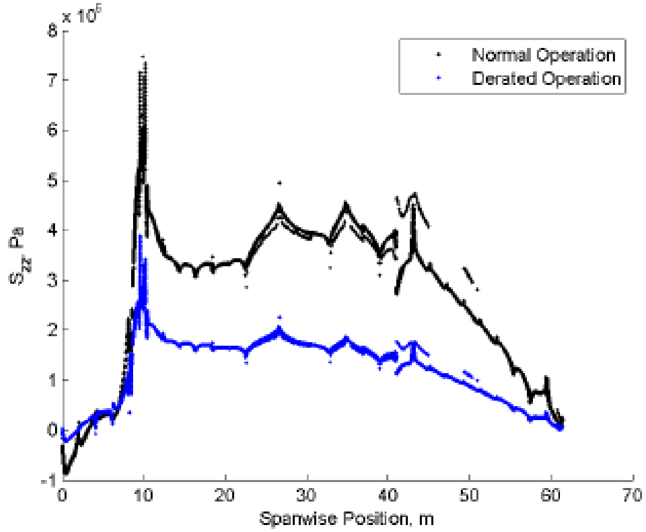


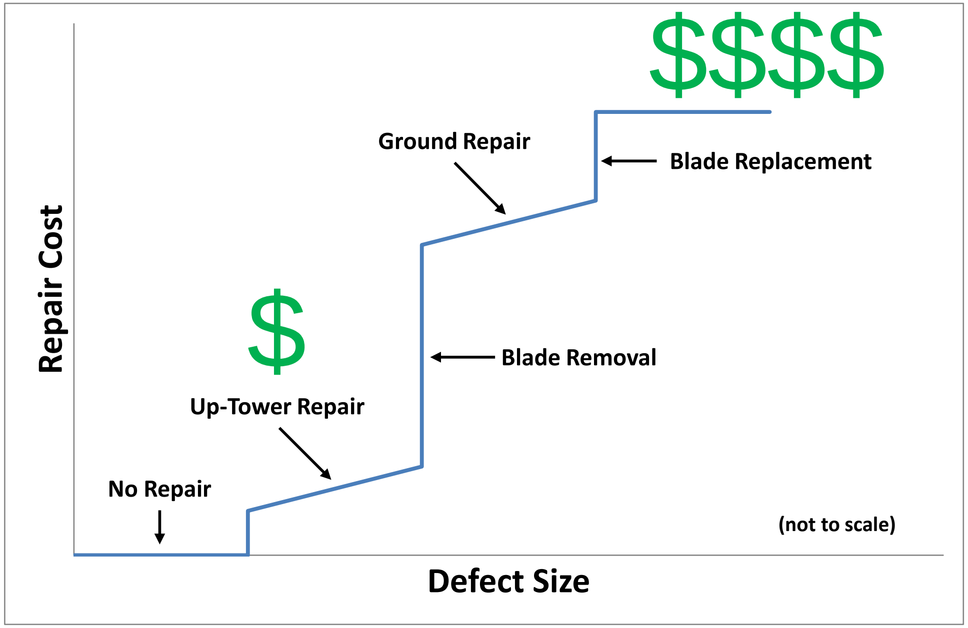
Figure 5: Stress results for σ_{zz} along the bond line for the baseline model during normal operation and derated to 50% power level.

Derating Strategy	A	B
Reduction in G_I	35%	70%
Reduction in G_{II}	33%	70%
Reduction in G_{III}	47%	63%

Reductions in SERRs for derated operation

[7] Optimized Maintenance Process Concepts

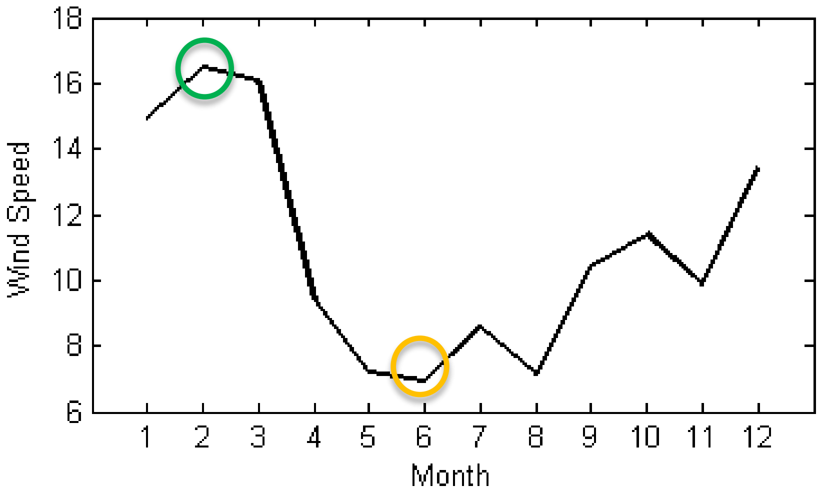
Opportunity to plan for cheaper repairs, optimize O&M processes



Repair costs depend on extent of damage and ease of accessibility.

[8] SHPM Economics Calculations

Parameter Study: Effects of varying (a) Derating approach, (b) Derating level, and (c) Monthly resource



The increased energy capture of derating ranges from 1.5% to 10.7% depending on level of derating and monthly variation in the wind resource,

Strong opportunity for return on investment of monitoring system

Derated in Month 6

Derated in Month 2

Derating for one week versus shutdown (20 cents/kW-hr):

Derating Level	Low Speed (7 m/s)	High Speed (16.5 m/s)
50% (A)	+$55,800 (+4.3%)	+$131,000 (+10.0%)
50% (B)	+$44,500 (+3.4%)	+$73,800 (+5.6%)

Results for a single 5MW turbine

[9] Damage Detection Strategies Tested under Variable Inflow Conditions: Inflow Variability Study (1)

- **Goal: Quantify effect of variable wind inflow on robustness of damage detection with a POD & POC simulations campaign**

Table 3: FAST Simulation Matrix for Each Blade Damage Type.

	Healthy	1m Dis-bond	2m Dis-bond	3m Dis-bond	4m Dis-bond	5m Dis-bond	10m Dis-bond
Wind Speed (3 - 25 m/s)	101	101	101	101	101	101	101
Horizontal Shear (30%, 60%, 90%)	303	303	303	303	303	303	303
Turbulence (A, B, KHTEST)	303	303	303	303	303	303	303

- **>16,000 simulations with varied extent of damage and varied inflow**
- **Sensitivities to varying inflow:**
  - **Wind speed, horizontal shear, and turbulence**
- **Effect on POD**
  - **POD improved in certain wind speed ranges (SHM optimization!)**

- **Waked flow is a subset of the varied inflow conditions: increased turbulence, horizontal shear, and velocity deficit**

POD = Probability of Detection

POC = Probability of Classification

[9] Damage Detection Strategies Tested under Variable Inflow Conditions: Inflow Variability Study (2)

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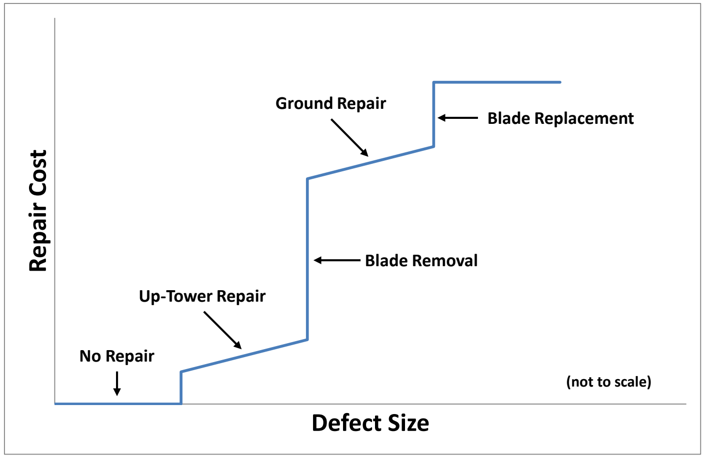
PURDUE UNIVERSITY

Ex. SW Disbond Case



State 1 State 2 State 3 State 4

Table 5: POD and POC for shear web disbond. The POD values are shown under PRESENCE OF DAMAGE and the POC values are shown in the other columns.

		PRESENCE OF DAMAGE		STATE 2 (1-2 m DISBOND)		STATE 3 (3-5 m DISBOND)		STATE 4 (>= 10 m DISBOND)	
		3 - 25 m/s	8.5 - 17.08 m/s	3 - 25 m/s	8.5 - 17.08 m/s	3 - 25 m/s	8.5 - 17.08 m/s	3 - 25 m/s	8.5 - 17.08 m/s
LAMINAR	Raw	84.16%	100.00%	84.16%	100.00%	83.33%	100.00%	84.16%	100.00%
	Weibull Weighted	77.24%	100.00%	77.24%	100.00%	77.16%	100.00%	77.24%	100.00%
30% SHEAR	Raw	74.26%	100.00%	72.79%	100.00%	69.11%	100.00%	72.79%	100.00%
	Weibull Weighted	78.07%	100.00%	77.95%	100.00%	77.55%	100.00%	77.95%	100.00%
60% SHEAR	Raw	44.55%	100.00%	35.73%	100.00%	36.61%	100.00%	36.17%	100.00%
	Weibull Weighted	60.18%	100.00%	58.30%	100.00%	58.61%	100.00%	58.46%	100.00%
90% SHEAR	Raw	15.84%	32.50%	10.82%	32.50%	11.29%	32.50%	10.98%	32.50%
	Weibull Weighted	25.19%	39.18%	23.21%	39.18%	23.58%	39.18%	23.34%	39.18%
A TURBULENCE	Raw	37.62%	75.00%	34.27%	75.00%	29.80%	75.00%	27.94%	75.00%
	Weibull Weighted	50.49%	74.99%	50.03%	74.99%	48.31%	74.99%	47.91%	74.99%
B TURBULENCE	Raw	45.54%	85.00%	42.39%	85.00%	36.07%	85.00%	33.82%	85.00%
	Weibull Weighted	62.86%	84.98%	61.73%	84.98%	59.38%	84.98%	59.65%	84.98%
KHTEST TURBULENCE	Raw	45.54%	80.00%	33.82%	80.00%	34.72%	80.00%	28.41%	76.00%
	Weibull Weighted	68.43%	88.06%	64.93%	88.06%	65.41%	88.06%	60.51%	85.76%

Detection probability reduced with turbulent inflow.

But, small reduction in detection in "optimized" wind speed range

[10] A Framework for SHPM Decision-making

Statistical framework is applied

1) **Damage detection and characterization:** Best estimate of damage state and its uncertainty (statistics) are estimated
2) **Local Sensitivity (state of health):** Best estimate of state of health and its uncertainty are estimated based on Step 1 in order to estimate remaining life (or unfavorable loading conditions)

Estimate of state of health / remaining life and its uncertainty → O&M Decisions

Operations decisions (e.g. control actions) are confirmed via aero-elastic simulation → ensure safe, revenue-optimizing modes of operation (i.e. normal operation, shutdown, or smart loads management / derating)

High-level Recommendations

I. **Health Monitoring & Inspection:** Coordination of the SHPM monitoring system with component inspection protocols is suggested – potential to reduce inspection needs/costs.

II. **System/Plant Life-cycle Design Improvements:** A turbine and/or wind plant should be “designed for inspection and monitoring”.

III. **Loads Monitoring:** Loads monitoring and loads forecasting should be incorporated into the SHPM system as it has potential to improve the SHPM system performance and reduce costs.

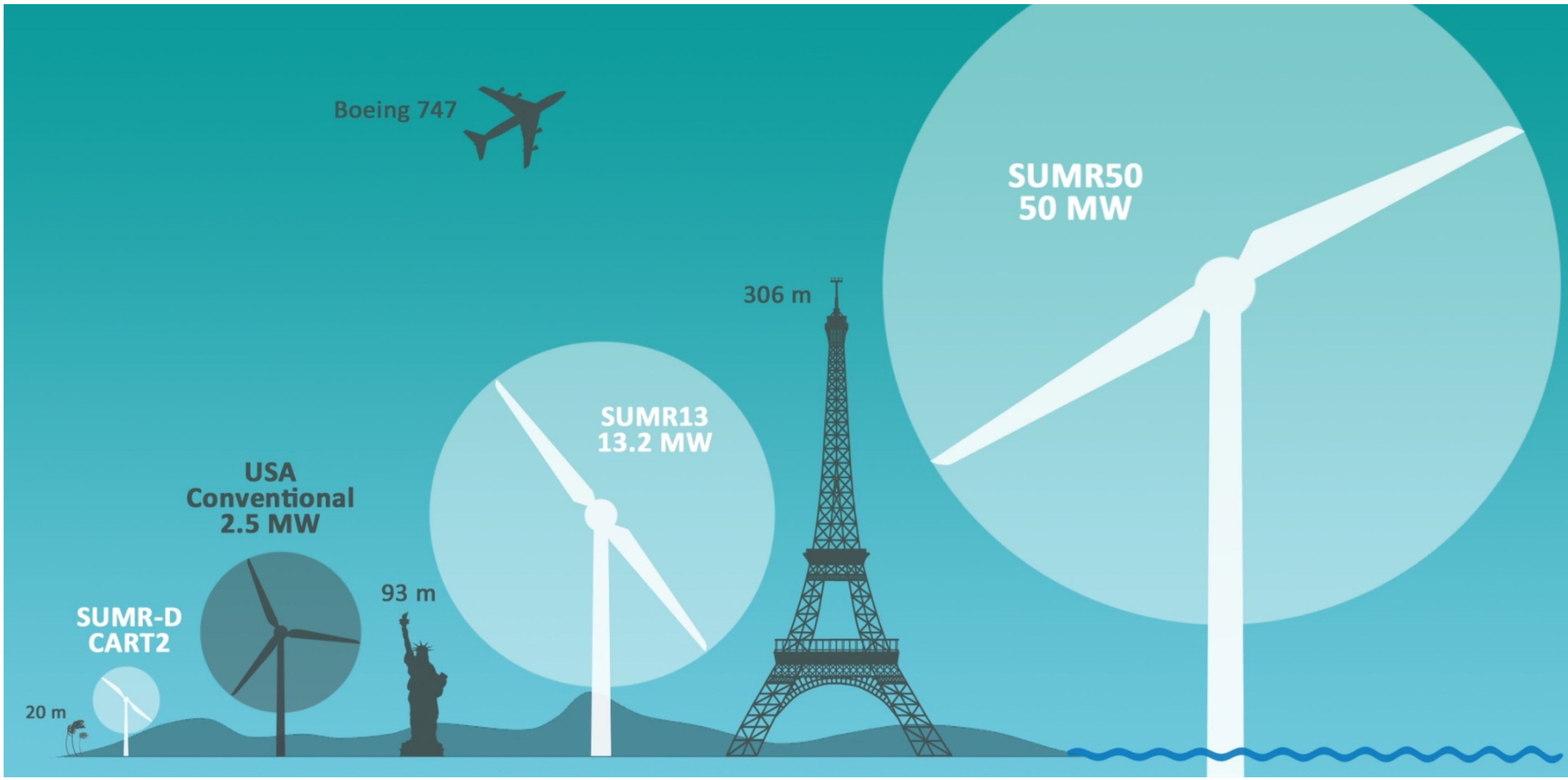
IV. **SHPM Validation by Modeling and Simulation:** A “blind” damage detection study to test damage detection strategies would be beneficial -- first a comprehensive modeling and simulation-based campaign and later through experimental validation.

V. **SHPM Validation in the Field:** Following validation by modeling and simulation, validation of SHPM and its various elements (e.g. damage detection, remaining life estimation, smart loads management (derating), optimized O&M processes, economics analysis) with experimental validation at laboratory then field scale (utility scale):

    I. to reduce uncertainty and reduce risk (of deploying new sensors & implementing new processes or corrective actions)

SUMR 50MW Extreme-scale

Targeting significant mass and cost savings



Major Project Findings
(Main Contributions and Areas for Future Work)

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10. A Framework for SHPM Decision-making

Publications

Sandia National Laboratories

1. Griffith, D.T., Yoder, N., Resor, B.R., White, J., Paquette, J., Ogilvie, A., and Peters, V., “Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies,” Proceedings of the European Wind Energy Conference Annual Event (Scientific Track), April 16-19, 2012, Copenhagen, Denmark.
2. Griffith, D.T., Yoder, N.C., Resor, B.R., White, J.R., and Paquette, J.A., “Structural Health and Prognostics Management for Offshore Wind Turbines: An Initial Roadmap,” Sandia National Laboratories Technical Report, December 2012, SAND2012-10109.
3. Myrent, N., Kusnick, J., Barrett, N., Adams, D., and Griffith, D.T., “Structural Health and Prognostics Management for Offshore Wind Turbines: Case Studies of Rotor Fault and Blade Damage with Initial O&M Cost Modeling,” Sandia National Laboratories Technical Report, April 2013, SAND2013-2735.
4. Myrent, N.J., Kusnick, J.F., Adams, D.E., and Griffith, D.T., “Pitch Error and Shear Web Disbond Detection on Wind Turbine Blades for Offshore Structural Health and Prognostics Management,” 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 8-11, 2013, Boston, MA, USA, AIAA-2013-1695.
5. Griffith, D.T., Yoder, N.C., Resor, B.R., White, J.R., and Paquette, J.A., “Structural Health and Prognostics Management for the Enhancement of Offshore Wind Turbine Operations and Maintenance Strategies,” Wiley Journal of Wind Energy, September 2013.
6. Myrent, N., Griffith, D.T., et al, “Aerodynamic Sensitivity Analysis of Rotor Imbalance and Shear Web Disbond Detection Strategies for Offshore Structural Health Prognostics Management of Wind Turbine Blades,” 32nd ASME Wind Energy Symposium, National Harbor, MD, USA, January 2014.
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