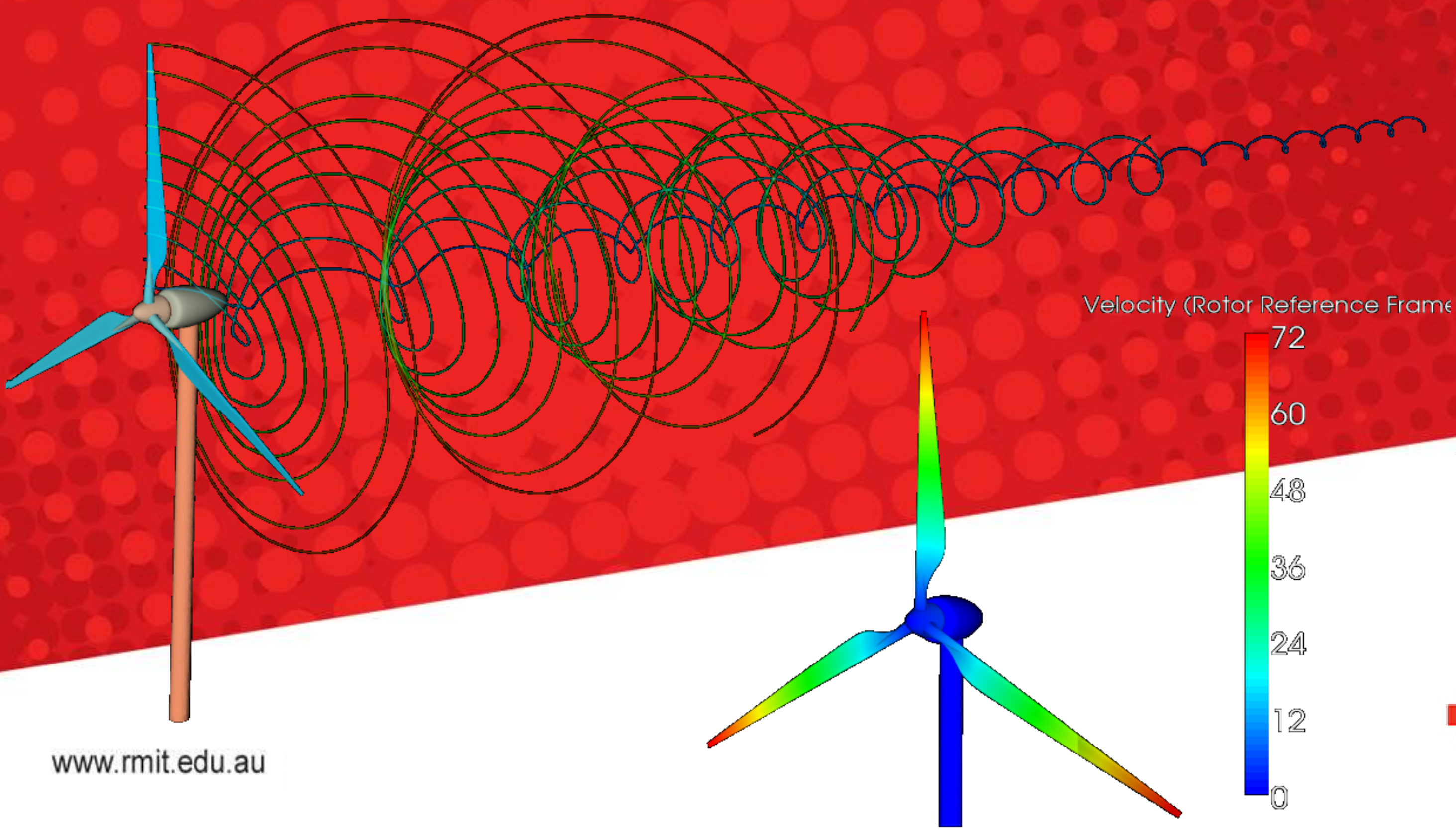
# Composite Wind Turbine Blade Modeling and Robust Design

P. Marzocca

*RMIT University, Australia, and Clarkson University, USA*

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# Presenter's WT Research Activities

## Composites WT Blades Aeroelastic and Robust Design

- Fixed- & Rotary-wings Aeroelasticity
- Composite Thin-Walled-Beam Models
- Composite Blade Design
- Composite Damage Progression

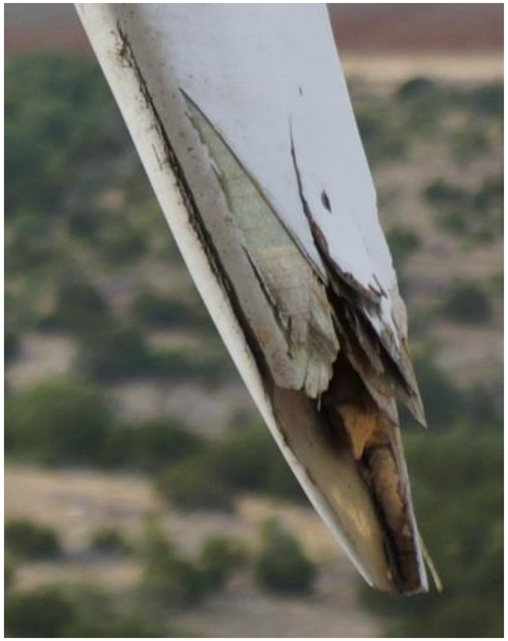
## Small-to-Large WT Technologies R&D

- Active/Passive Flow Control Strategies
- Structural Health and Load Monitoring
- Wind Tunnel Testing
- Blade/Components Structural Testing
  - Static, Fatigue, Modal


**POCs:** Daniel Valyou, Co-Director and Facility Manager, CECET Blade Test Facility, Clarkson University, Clarkson Ave., Potsdam NY 13699, phone: (315) 268-3796, mail: valyoudn@clarkson.edu
Kerop Janoyan, Co-Director CECET Blade Test Facility, Clarkson University, kerop@clarkson.edu

# Current Challenges with Distributed WT Blades: Quality and Reliability

- Quality and reliability, affecting strength and blades lifetime
  - Manufacturing process control
  - Methods and models describing production defects effects
  - Methods to evaluate imperfections and damage progression
- Composite Blades: Improve stiffness, tensile strength in the fiber direction, compressive strength
- Methods to improved fatigue life prediction



# New Materials for WT Blades: What's Coming into the Market

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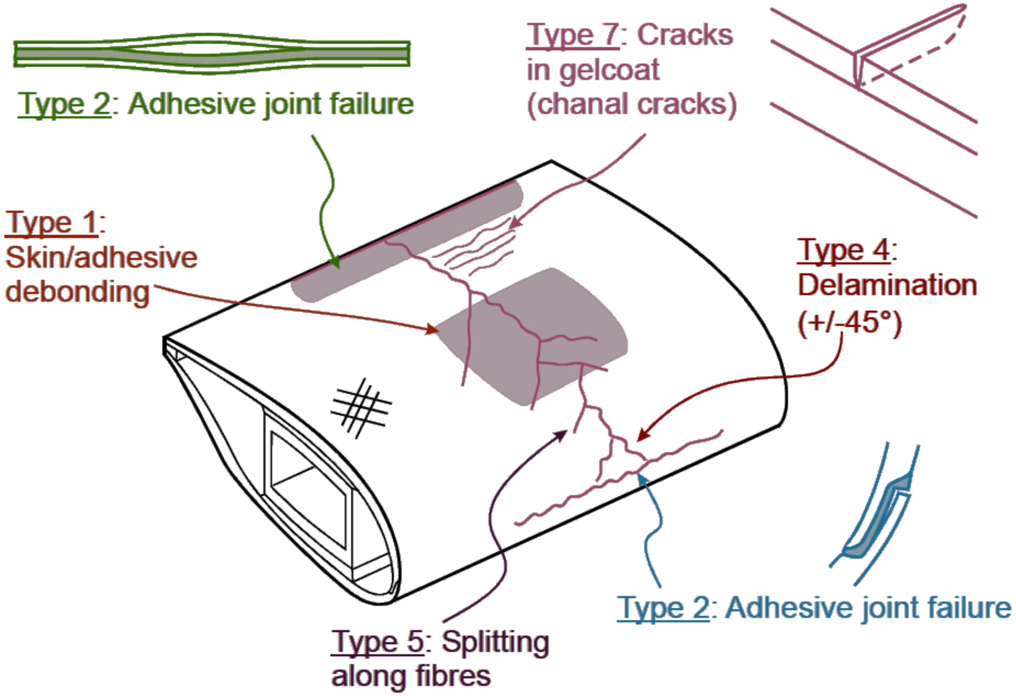
- High-strength/high-stiffness fiber reinforced composites, glass-carbon mixture
- Light-weighting, low-costing solutions
- Engineered materials for strength, stiffness, toughness, and adhesion
- Increased tensile and shear strength in the out-of-plane direction and compressive strength
- New energy efficient manufacturing processes for new materials
- Recyclability: Thermosetting resins not recyclable. Thermoplastic resins have high toughness, are recyclable (high temperatures processes)
- Environment considerations: Renewable materials including natural cellulose fibers for reinforcement and bio-based resins
- Natural fibre-reinforced polymer Fiber treatment and coating technologies to minimize hydrophobic matrix/hydrophilic fiber issues.

# Composite Damage & Failure Models: A Plethora of Possibilities

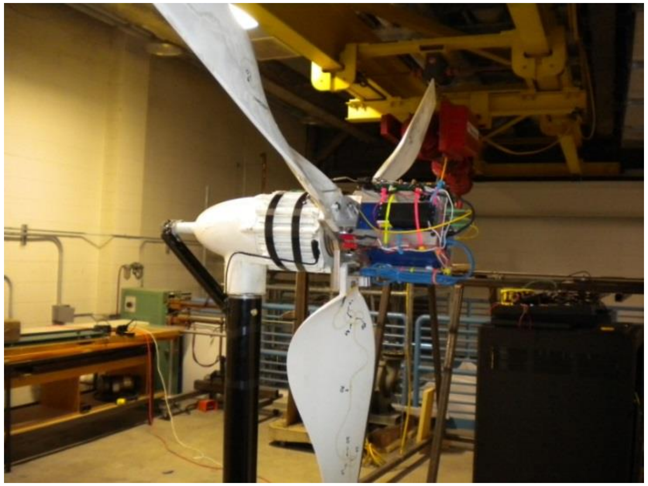
- Type of load
  - Monotonic
  - Cyclic
- Damage and fracture behaviour models
  - Parametric
  - Phenomenological
  - Micromechanical
  - Probabilistic




- Modes of failure
  - Fiber (tension, compression, shear)
  - Matrix (transverse tension/compression, shear or combination)
  - Lamina vs. constituents (matrix and fiber) properties

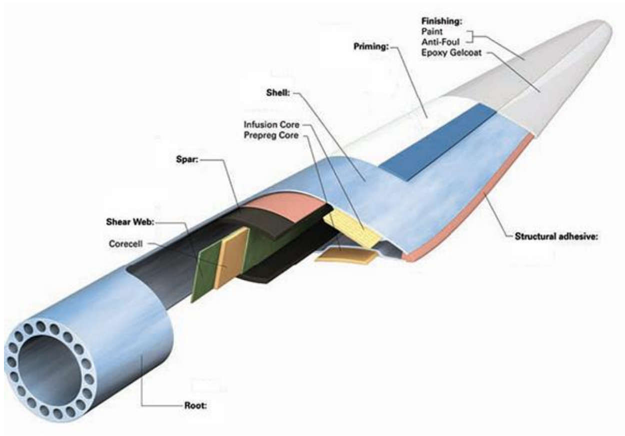
# The Importance of NDI & SHM: Is it truly Important?

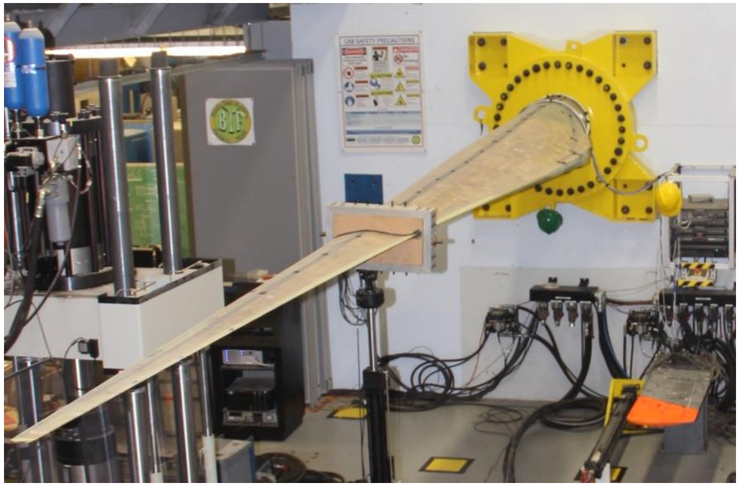
- Zero maintenance if possible: Early stage defect/damage detection with cost-effective and reliability solutions.
- Condition-based vs. scheduled-based maintenance
- Thick sandwich and laminated composites present challenges for NDI
- Field Reliability: Monitor blade degradation while in service to predict remaining lifetime (support for damage models)
  - Low cost SHM systems, including acoustic emission, optical fibers, etc.
  - Effect of lightning strikes, ice, and hailstorms



# Aero-Structural Design & Testing

- Weight reductions with fiber composite blades with improved structural design
- Lighter/optimized blades to avoid dynamic loading / fatigue failures
- Develop practical approaches for achieving damage tolerant design
- Exploit anisotropic nonsymmetrical laminates (bending and twist coupling)
- Aerodynamic profile optimization
- Pitch control mechanism is costly and generally slow to respond to gusts. Solution: "smart blades"?
- Blade testing for design improvement and quality assurance



# Aeroelasticity of Damaged Rotor TWB & Progressive Failure Analysis

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- Composite Thin-Walled Beam (TWB) Finite Element (FE) model including Progressive Failure Analysis (PFA) capabilities
- Semi-Analytical Finite Element Models via Progressive Polynomial and B-Splines Reduction of Modal Data (Poly/B-SAFE)

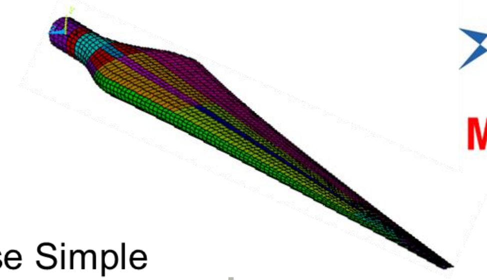
Based on FEM Model

SIMULIA

ANSYS

AlphaSTAR

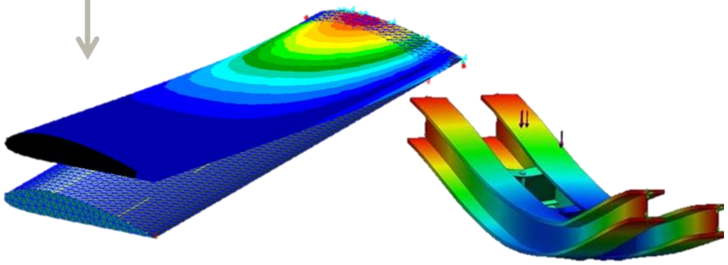
MSC Software



Use Simple Modal Analysis

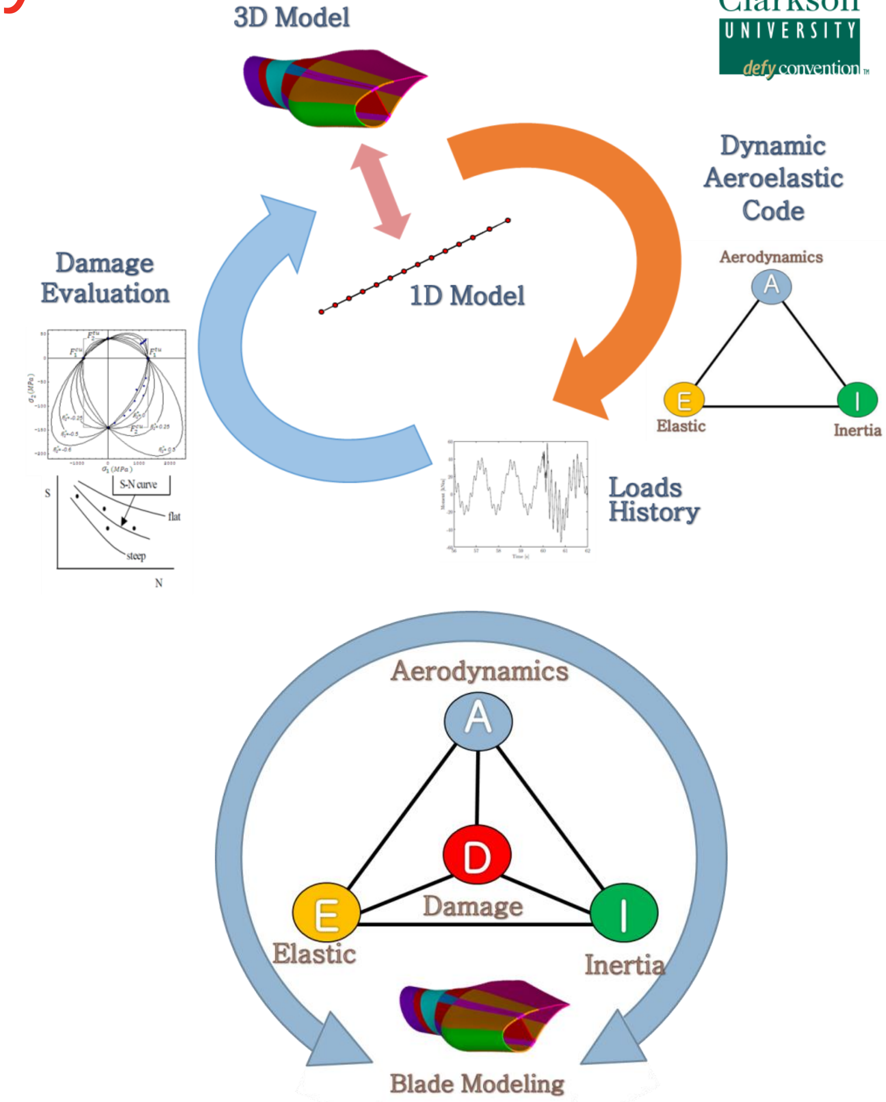
To extract eigenvalues and vectors

Simple approach to obtain Displacement, strain and stress analytical function to evaluate static, dynamic, aeroelastic behavior of structural systems

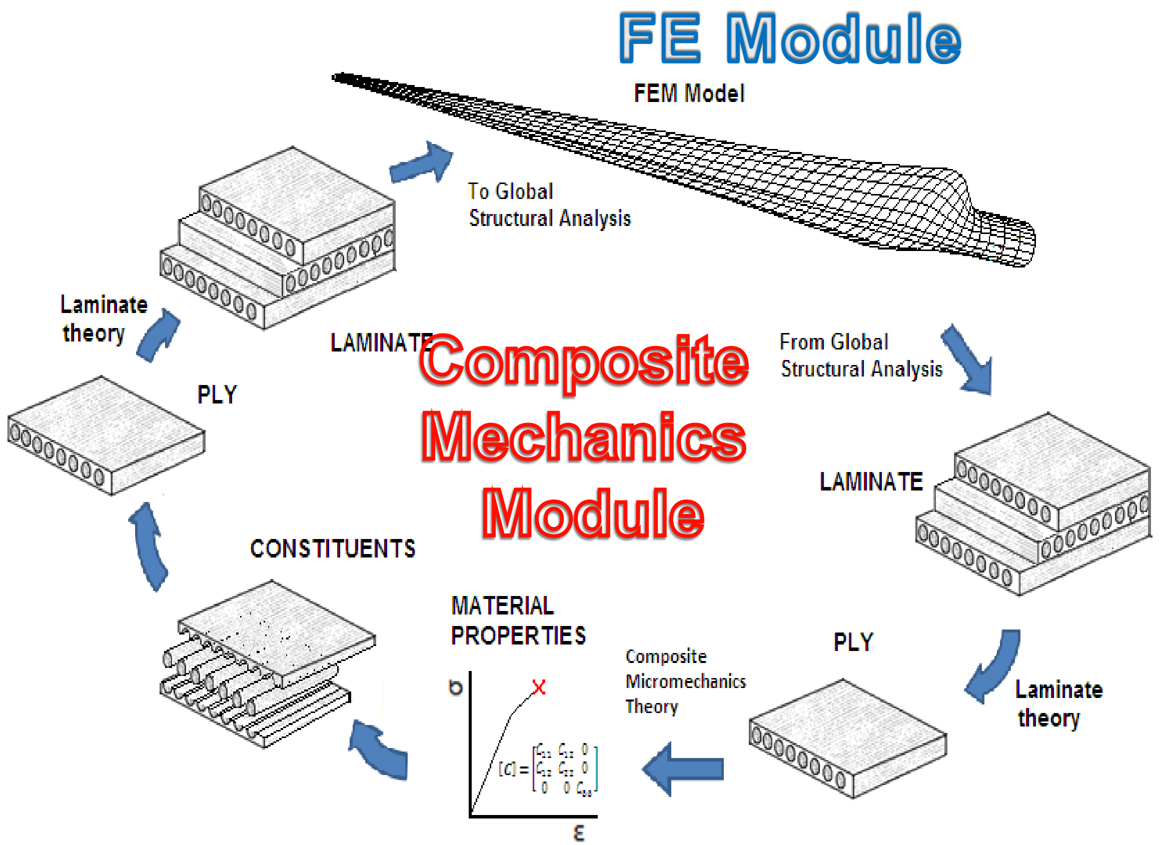


# Composite Thin-Walled Beam & Progressive Failure Analysis

- Progressive Failure Analysis (PFA) into a Thin-Walled Beam (TWB) FE model
- TWB is a 1D model used to reproduce the structural behavior of a more complex 3D shells or solid FEM
- TWB with shell capabilities, retains composite lamination information to recover stresses/strain and deformations
- Composite failure criteria can be applied
- TWB and GENOA® by ASC share same PFA algorithm
- Aeroelastic simulations enables



# PFA Based on GENOA® CODSTRAN by AlphaStar Corp.

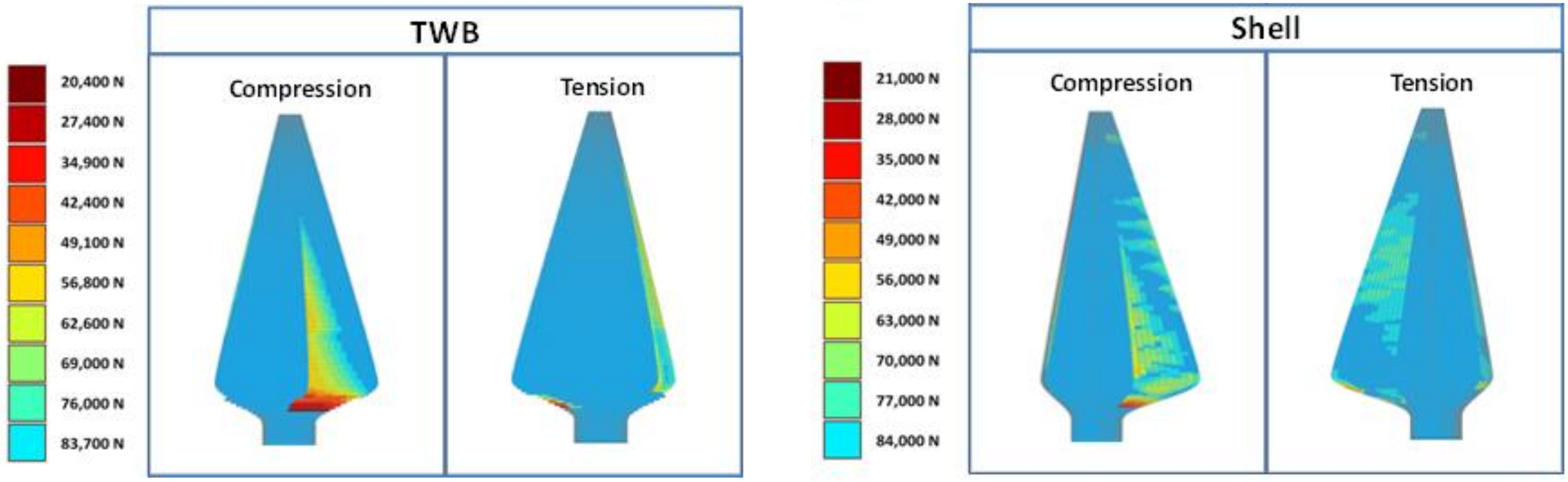



Progressive Failure Analysis (PFA) cycle

- GENOA® expands the capabilities of commercial FEA packages
- Multi-Scale (Micro-macro) Progressive Failure Analysis (PFA) capability
- TWB and GENOA® share same PFA algorithm

# PFA Static Simulations Comparison with High Fidelity

Progressive Failure for layer 6 (Balsa).




SANDIA NPS-100 - TPI Composites blade

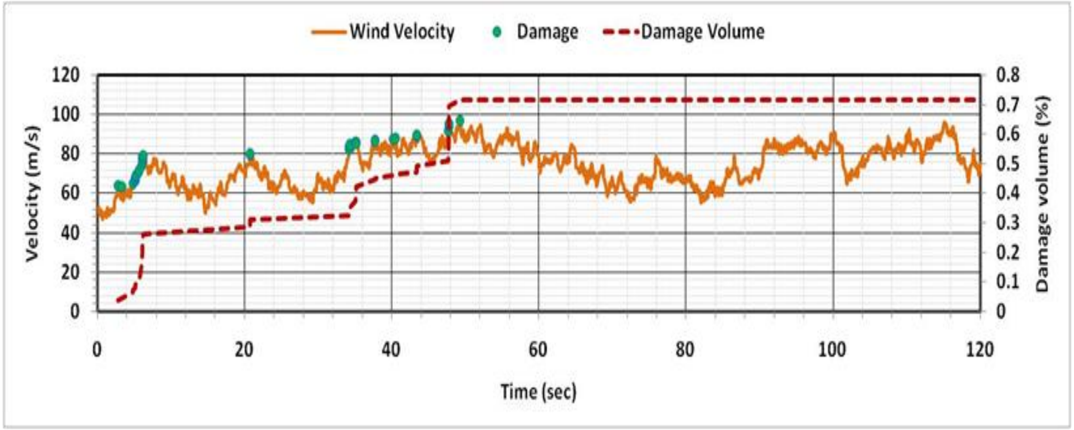
ANSYS: 3353 elements, 9926 nodes, **55,356 DOF**
TWB: 30 beam elements, 31 nodes, **217 DOFs**

2% error in predictions with model reduction to 0.4% DOF

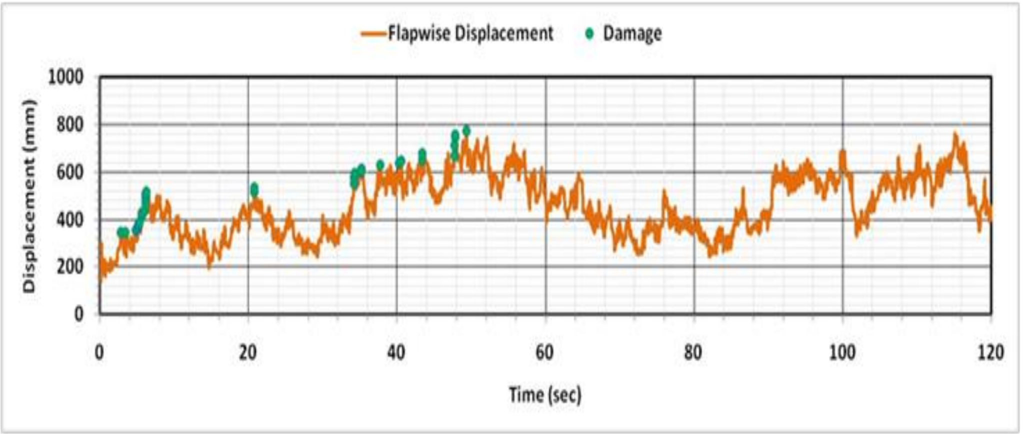
# Rotor Facing Class 5 Hurricane

- Gravitational, centrifugal, and aerodynamic loads included in dynamic aeroelastic simulation
- Aerodynamic loads based on Blade Element Momentum (BEM) theory

**Case 1:** Parked rotor facing Class 5 hurricane

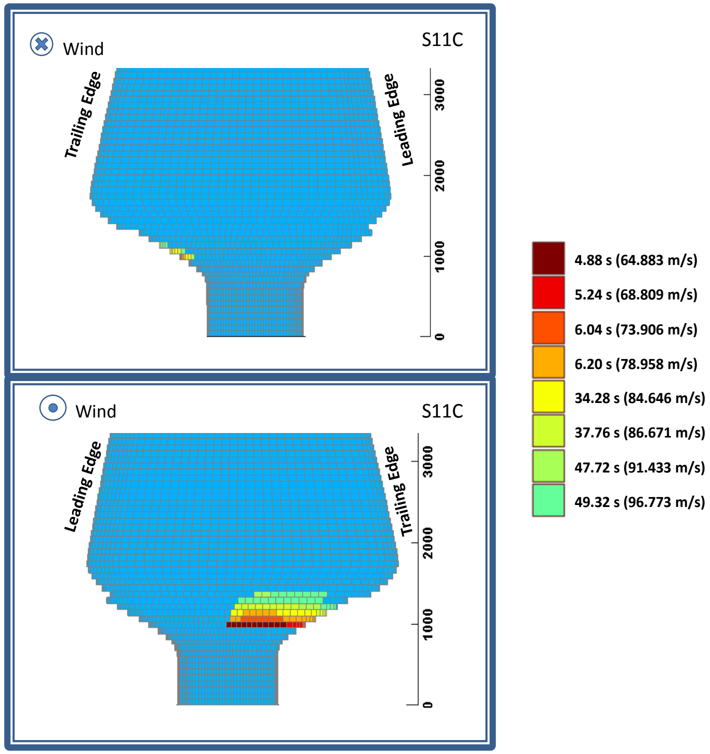



Wind speed time series and damage volume



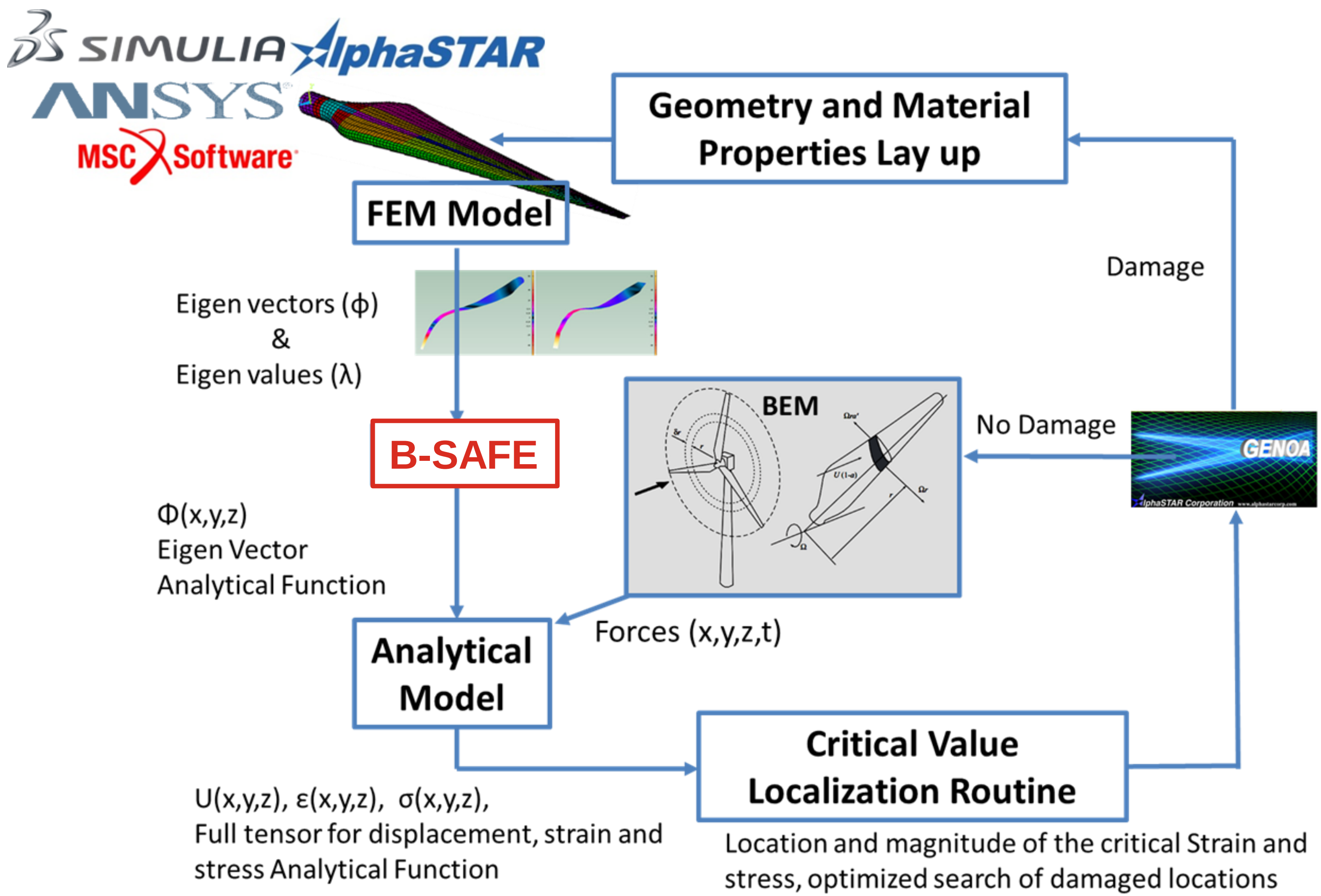

Flapwise displacement

PFA Layer 6 (Balsa)

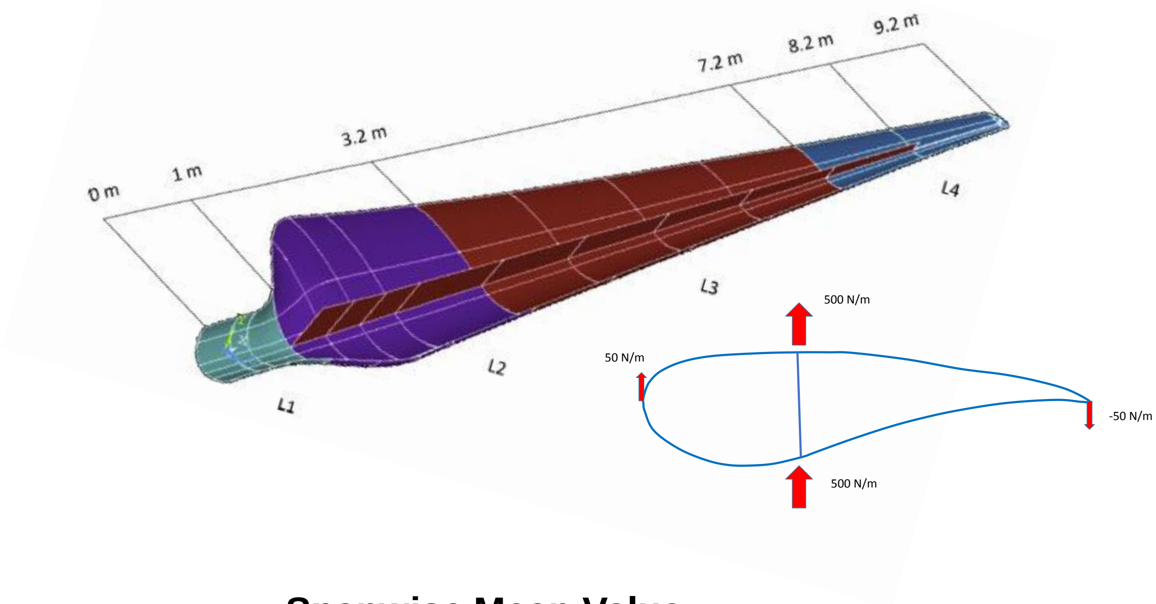



Progressive Failure Analysis of layer 6 (Balsa)

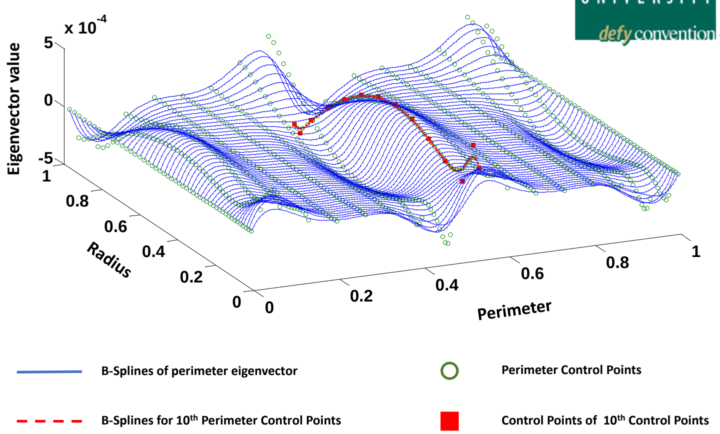
# Why B-SAFE?
# B-SAFE Working Principles

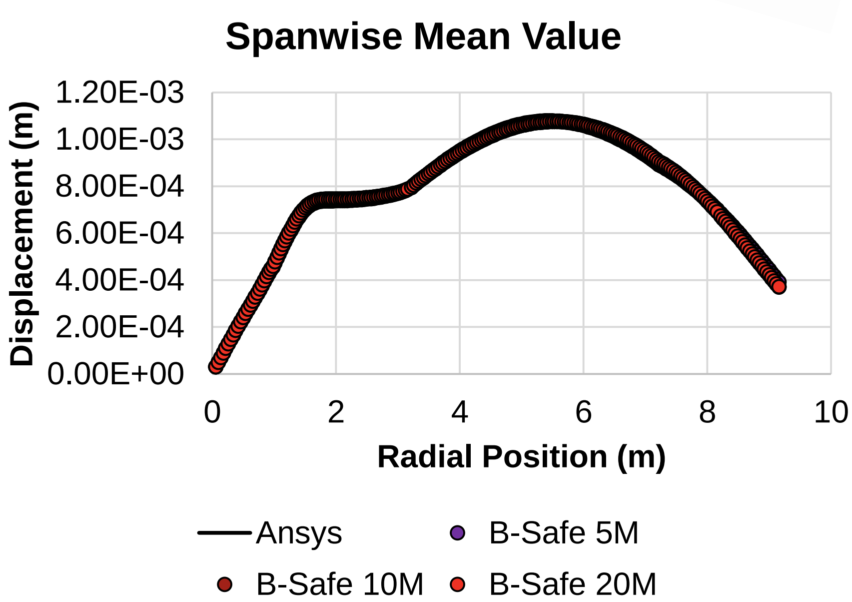


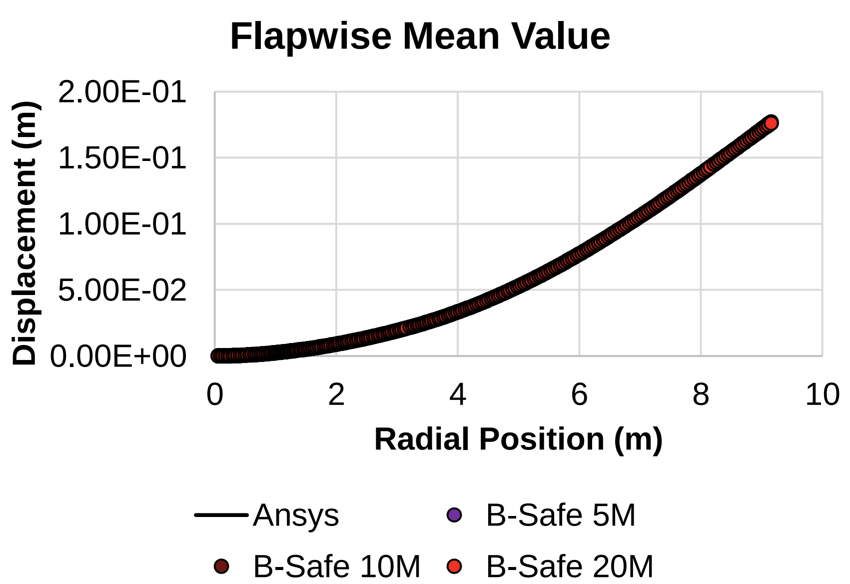
# B-SAFE Case Study




## Eigen-mode description

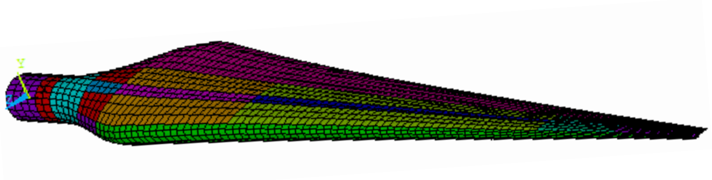


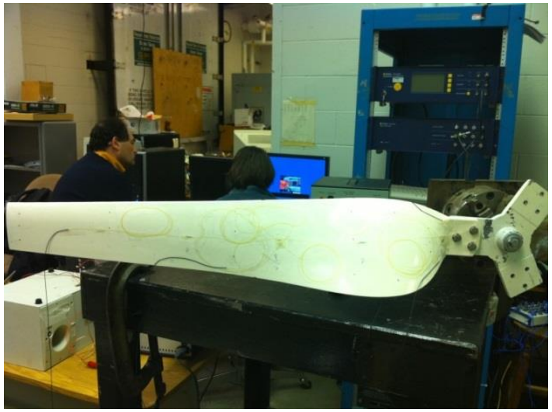



# Wind Turbine Short Term Challenges

- Materials. Currently used vs. new materials including NFRP. Recyclability
- Aero-structural design and testing. Emphasis on robust design, durability and damage tolerance and structural testing
- Aerodynamic design. Loading, environmental conditions to uncertainties qualification
- Non-Destructive Inspection and Structural Health Monitoring. At all levels from production to operation
- Manufacturing processes. Including autoclave vs. out-of-autoclave, microwave bonding and joining; Automated fabric laying, automated tape laying, pultrusion and additive manufacturing processes
- Energy efficient, Environmental friendly & Cost Reduction





# Contact Info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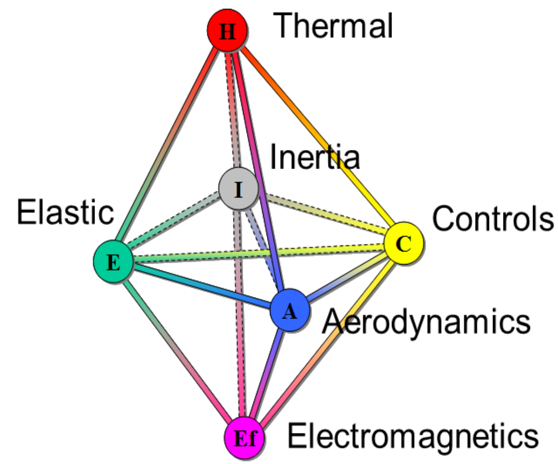
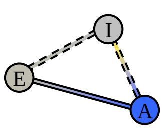
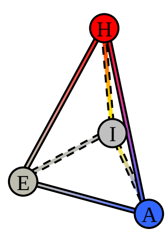


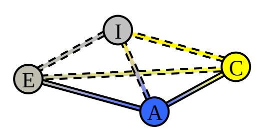

- Aero-elasticity



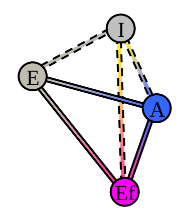

- Aero-thermo-elasticity




- Aero-servo-elasticity



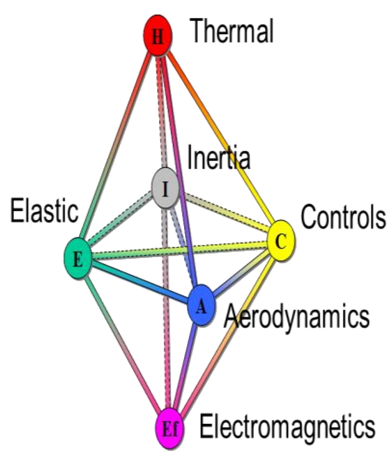

- Aero-magneto-elasticity

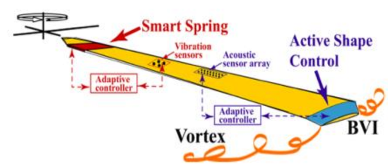


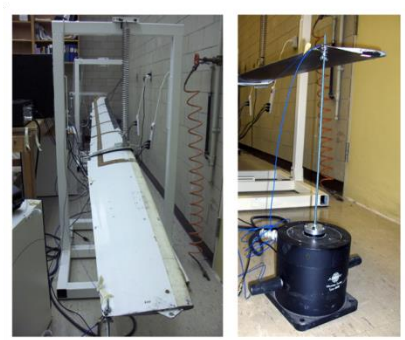
# Extra slides

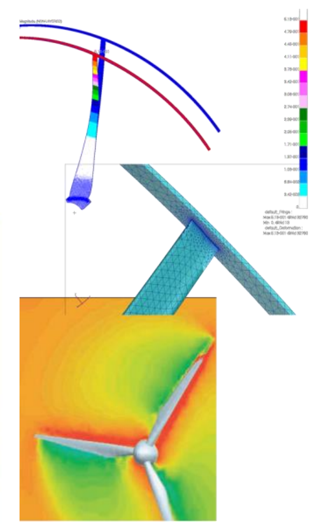
# Presenter Short Bio

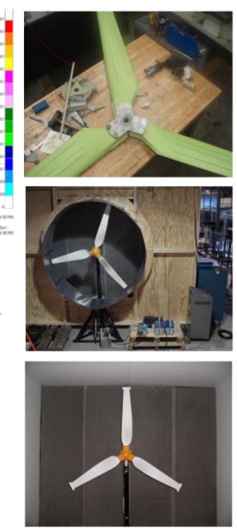
| | |
|---|---|
| **1996** | BS, MS Aeronautical Engineering; Politecnico di Torino, Italy |
| **2001** | PhD Aerospace Engineering, Politecnico di Torino, Italy |
| **2003** | PhD Visiting / PostDoc, Engineering Science & Mechanics, Virginia Tech USA |
| **2015** | Assistant, Associate, Full Professor,<br>Mechanical and Aeronautical Engineering Department, Clarkson University, USA |
| **2015** | Deputy Head of Aerospace and Aviation, School of Aerospace, Mechanical and Manufacturing Engineering, Royal Melbourne Institute of Technology, Australia |





# WT Aeroelastic Codes

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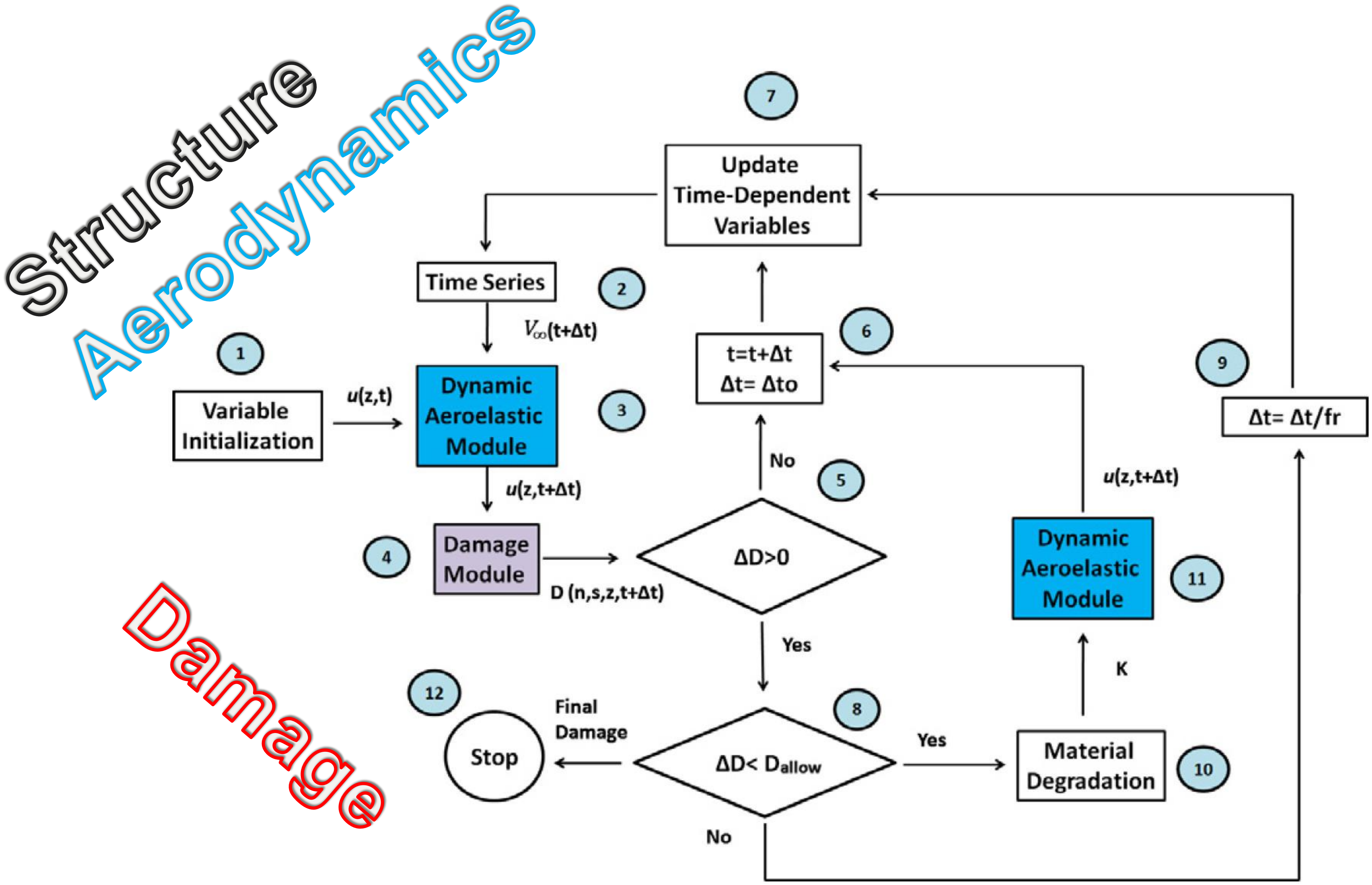
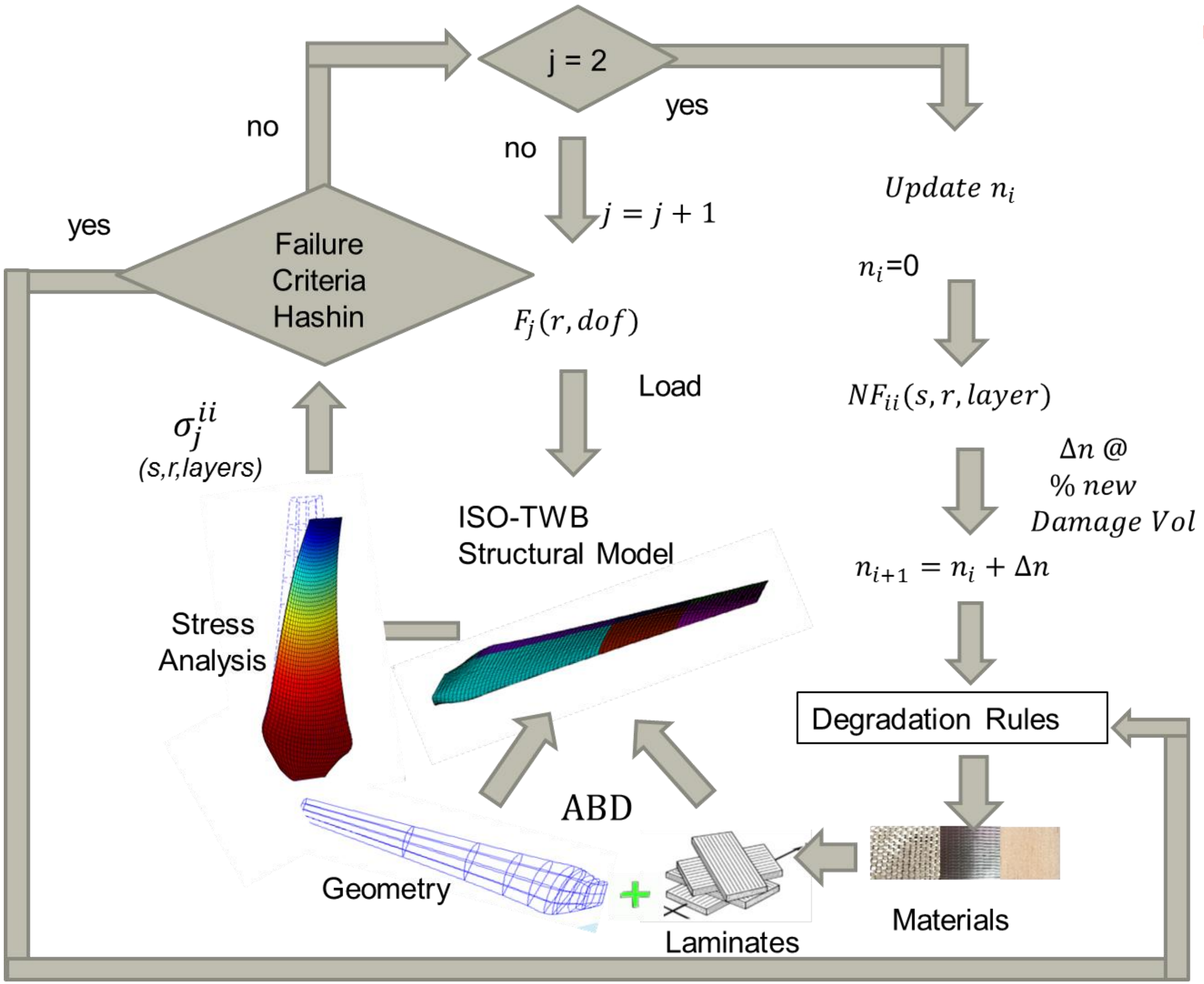
| Name | Participants | Structural dynamic model | Aerodynamic model |
|---|---|---|---|
| ADAMS/WT | The ADAMS package is developed by Mechanical Dynamics, Inc., and the add-on Module WT is developed under contract to the NREL | Multibody dynamic | BEM theory |
| Alcyone | CRES and NTUA, Gr | FEM | Free wake panel method |
| BHawC | Siemens | Co-rotaing elements | BEM theory |
| DUWECS | TUD, NL | Multibody dynamic | BEM theory |
| FAST | NREL and Oregon State University, US | Modal approach | BEM theory |
| FLEX5 | Technical University of Denmark, DK | Modal approach | BEM theory |
| FLEXLAST | Stork Product Engineering, SPE, NL | Multibody dynamic | BEM theory |
| GAROS | | Modal approach | BEM theory |
| GAST | NTUA, Gr | FEM | Free wake panel method |
| GH Bladed | Garrad Hassan and Partners, Ltd. UK | Modal approach | BEM theory |
| HAWC | Risø, DK | FEM | BEM theory |
| HAWC2 | Risø, DK | Multibody Dynamic | BEM theory |
| PHATAS | ECN, HL | Modal approach for support structures and FEM for Rotor and Nacelle | BEM theory |
| TURBU | ECN, HL | Multibody Dynamic | BEM theory |
| TWISTER | Stentec B.V. | | BEM theory |
| VIDYN | Teknikgruppen AB, Swed | Modal approach | BEM theory |
| YawDyn | University of Utah and NREL, US | | BEM theory |

Notes: NREL–National Renewable Energy Laboratory, US

# Aeroelastic Code with Damage Progression Capabilities

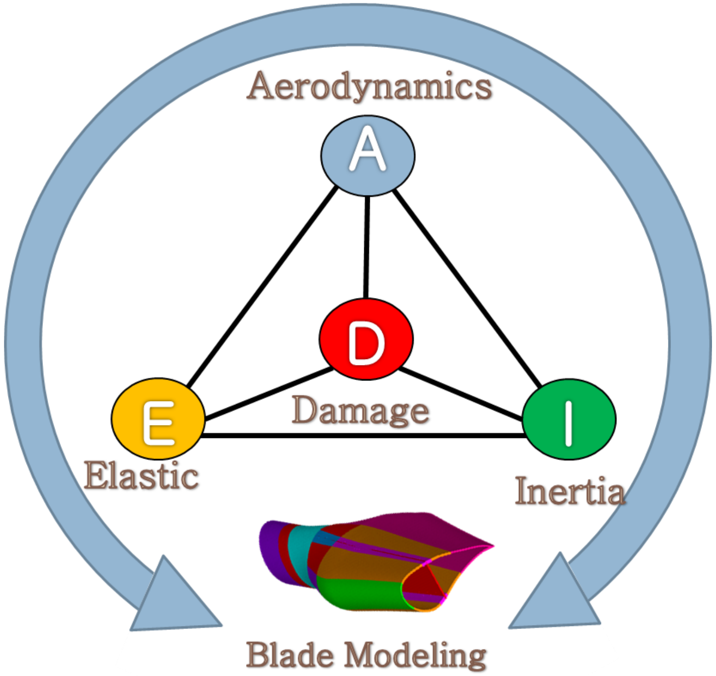


# Iso-geometric -TWB



# B-SAFE Potential Capabilities

- Static and dynamics analysis by evaluation instead of FE type calculations
- FSI analysis including
  - Load alleviation and redistribution
  - Gust and buffeting response
  - Control effectiveness
  - Divergence and flutter predictions
- Tailoring lamination evaluations
- Shear and twist center location evaluations
- Optimize search for failure
  - Damage progression in conjunction with FSI
  - FE based PFA capabilities
- Robust design and structural optimization



# Clarkson Blade Test Facility

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Blade Test Facility BTF Clarkson-CECET

| Static Test Frame | Fatigue Test Frame |
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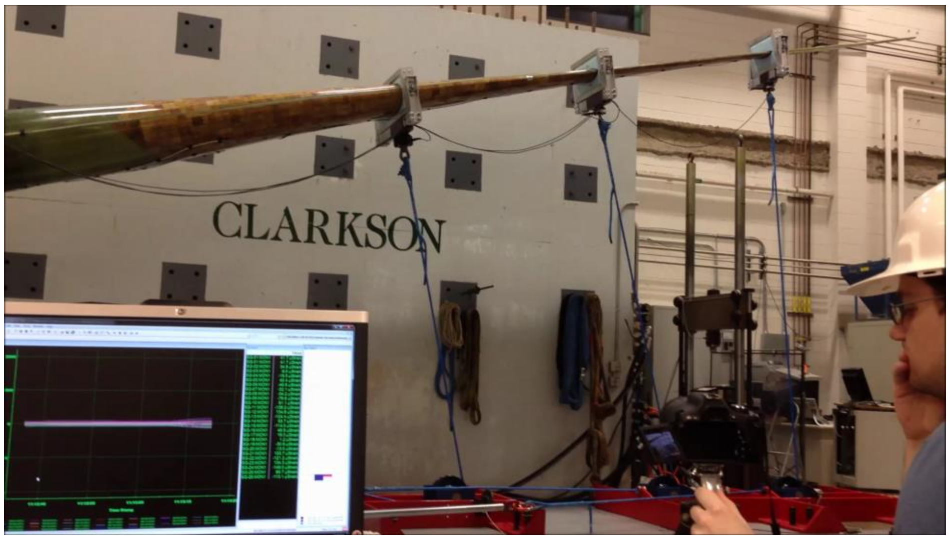
|  |  |



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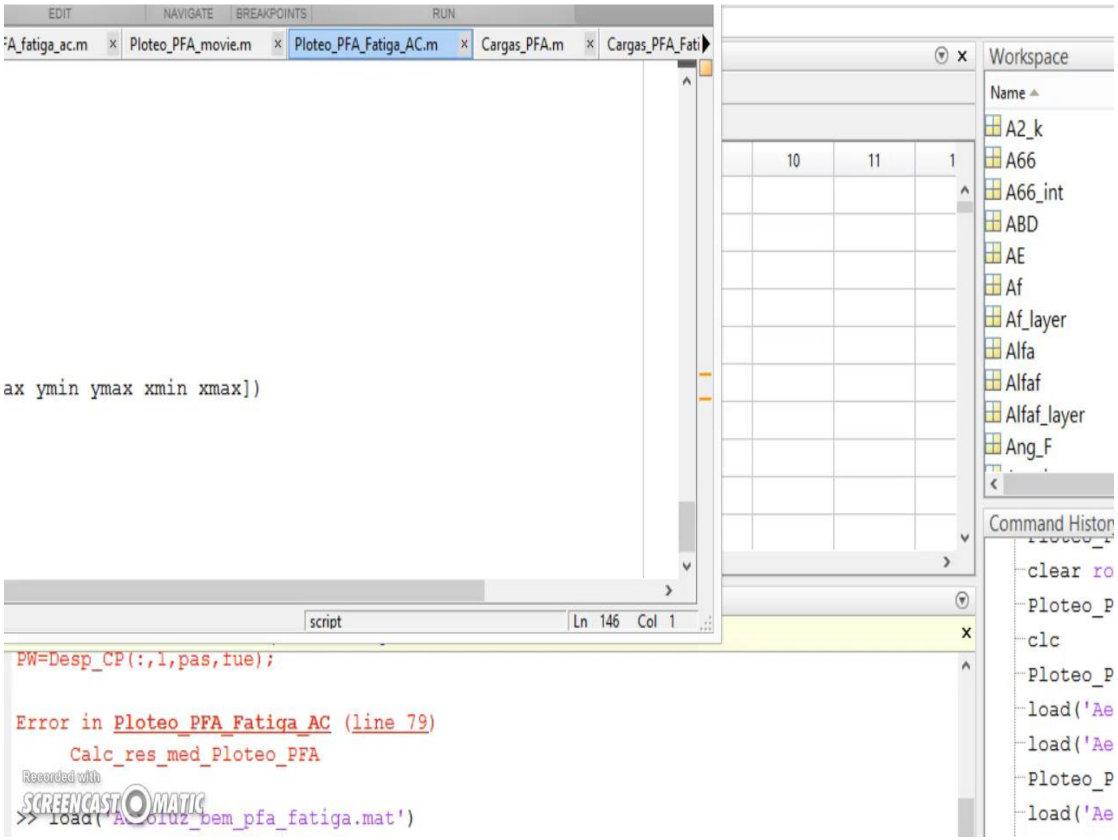
Kerop Janoyan, Co-Director CECET Blade Test Facility, Clarkson University, kerop@clarkson.edu

# Constant Amplitude Progressive Failure Analysis (video)




# Flow Structure Interaction and PFA

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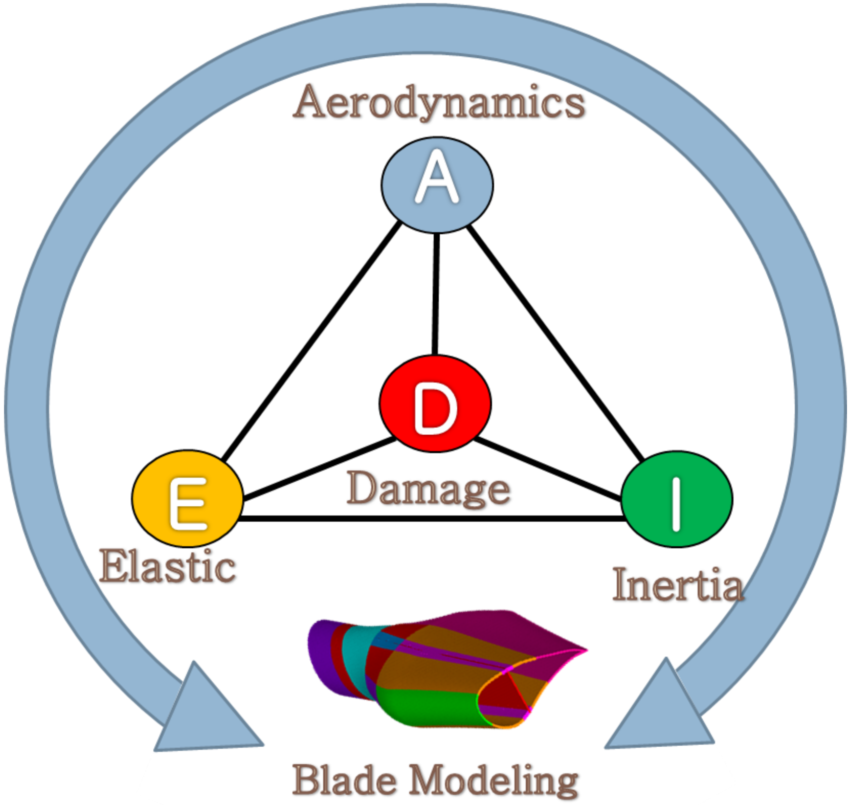
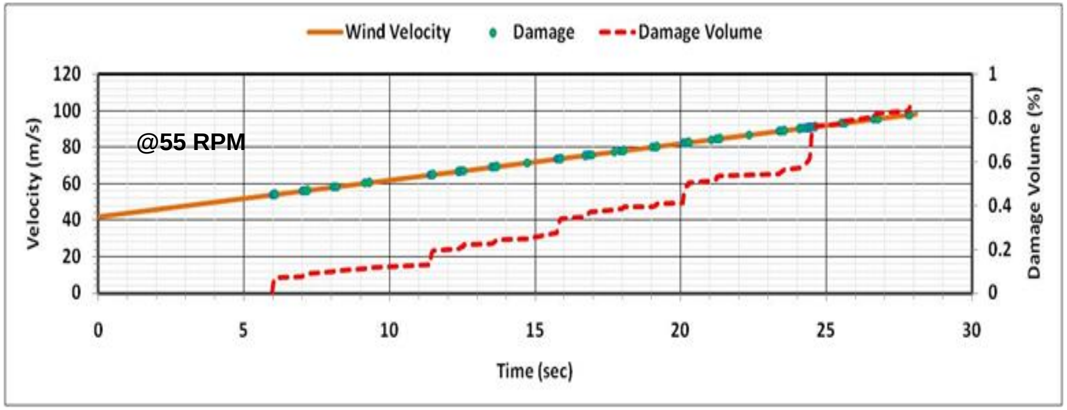


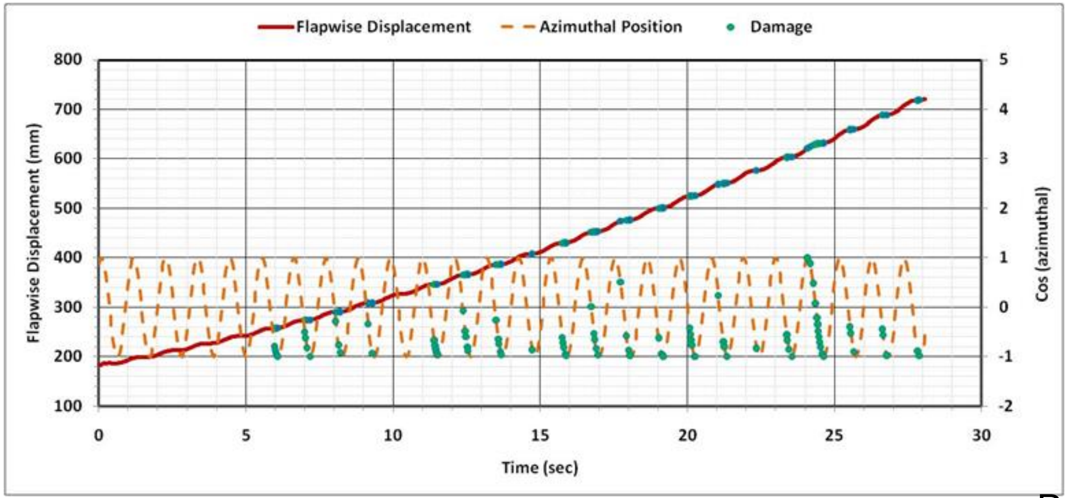

- Composite TWB FE model with PFA capabilities
- Gravitational, centrifugal, and aerodynamic loads included in dynamic aeroelastic simulation
- Aerodynamic loads based on Blade Element Momentum (BEM) theory

# Rotor Facing Increasing Speed Winds

**Case2:** Wind speed ramp at constant rotor shaft frequency (55RPM)

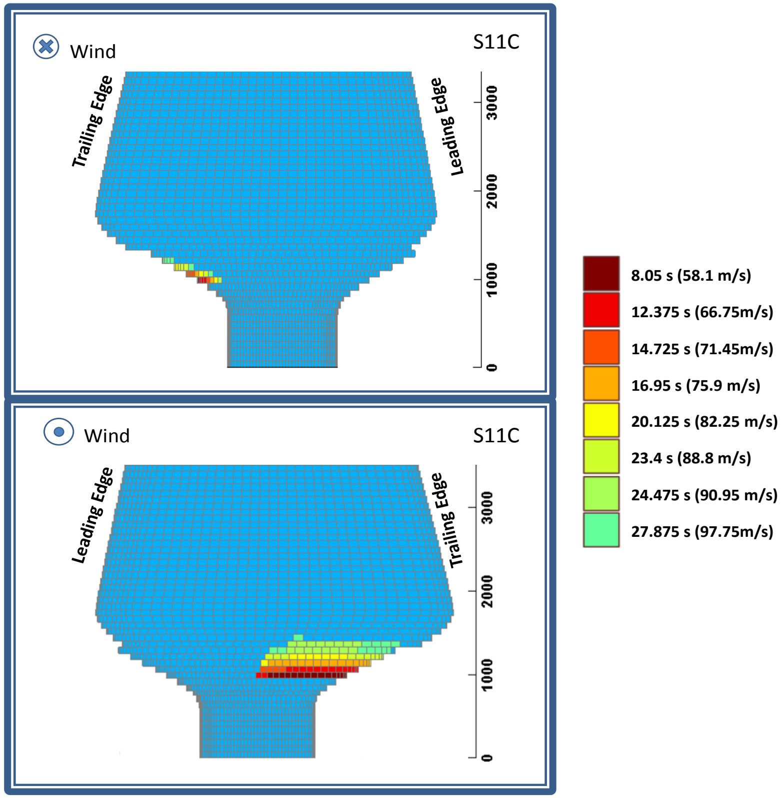



Wind speed time series and damage volume




Flapwise displacement and azimuth position of the blade

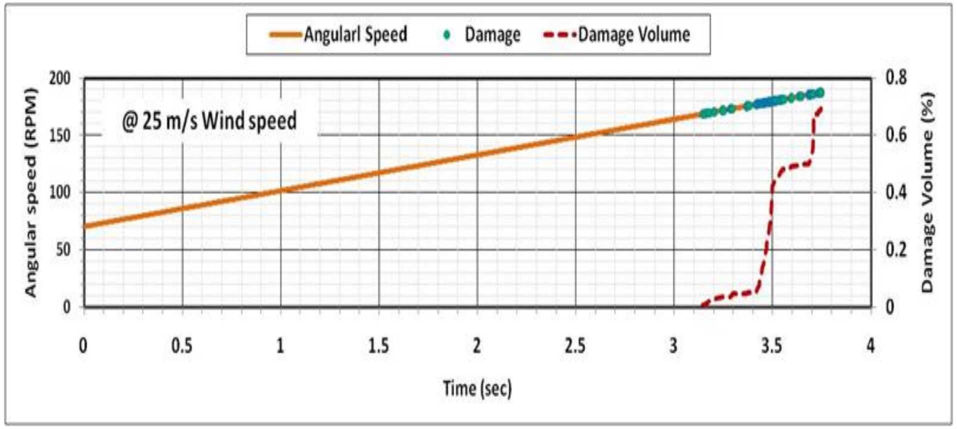
## PFA Layer 6 (Balsa)



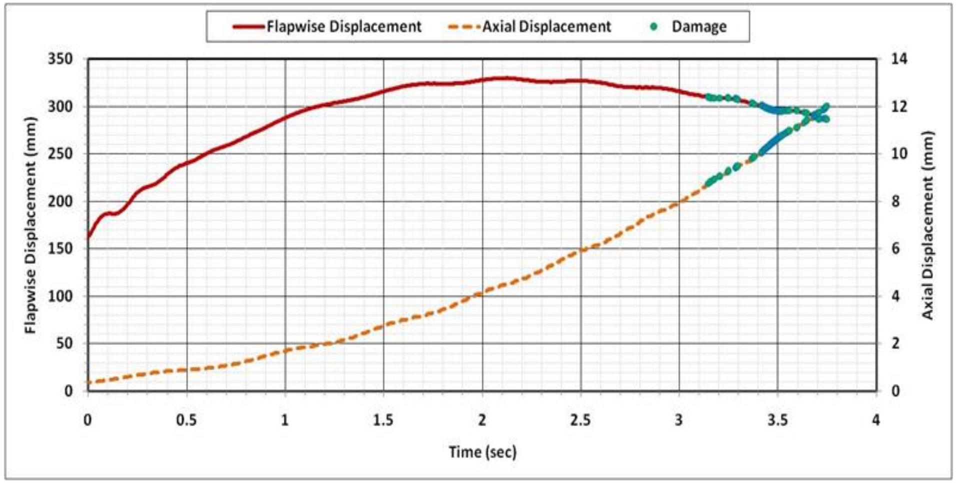

Progressive Failure Analysis of layer 6 (Balsa)

# Rotor with Loss of Electric Load

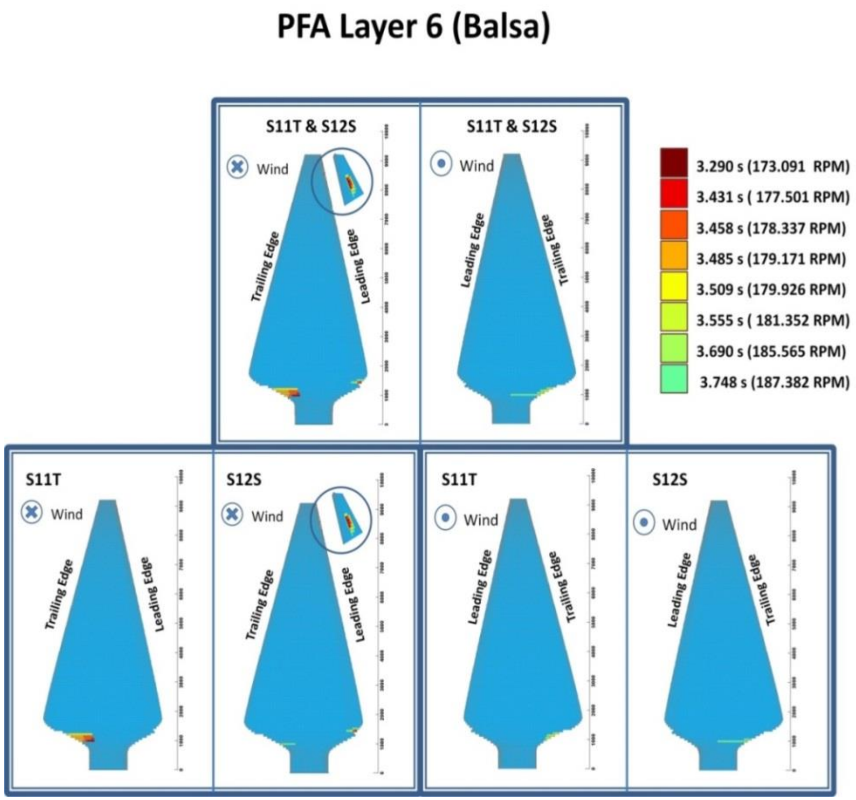
**Case 3:** Constant Wind Speed (25 m/s)




Wind speed time series and damage volume




Flapwise and Spanwise displacement of the blade




Progressive Failure Analysis of layer 6 (Balsa)

# Why B-SAFE?

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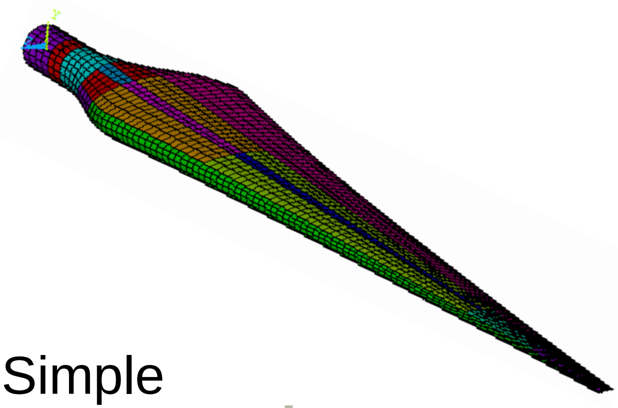
Based on FEM Model

SIMULIA

ANSYS



AlphaSTAR

MSC Software

Use Simple
Modal Analysis

To extract
eigenvalues
and vectors

Simple approach to obtain
Displacement, strain and stress
analytical function to evaluate
static, dynamic, aeroelastic
behavior of structural systems