Composite Wind Turbine Blade Modeling and Robust Design

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RMIT University, Australia, and Clarkson University, USA
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

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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

- 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

- 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

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

Use Simple Modal Analysis

To extract eigenvalues and vectors
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.

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

Progressive Failure Analysis (PFA) cycle
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

Progressive Failure Analysis of layer 6 (Balsa)
Why B-SAFE?

B-SAFE Working Principles

FEM Model

Geometry and Material Properties Lay up

Eigen vectors ($\phi$)
Eigen values ($\lambda$)

B-SAFE

Analytical Model

$\Phi(x,y,z)$
Eigen Vector
Analytical Function

$U(x,y,z), \varepsilon(x,y,z), \sigma(x,y,z)$,
Full tensor for displacement, strain and stress Analytical Function

Forces ($x,y,z,t$)

Critical Value Localization Routine

Location and magnitude of the critical Strain and stress, optimized search of damaged locations

Damage

No Damage
B-SAFE Case Study

Spanwise Mean Value

- Ansys
- B-Safe 5M
- B-Safe 10M
- B-Safe 20M

Flapwise Mean Value

- Ansys
- B-Safe 5M
- B-Safe 10M
- B-Safe 20M

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**
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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, 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

<table>
<thead>
<tr>
<th>Name</th>
<th>Participants</th>
<th>Structural dynamic model</th>
<th>Aerodynamic model</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAMS/WT</td>
<td>The ADAMS package is developed by Mechanical Dynamics, Inc., and the add-on Module WT is developed under contract to the NREL</td>
<td>Multibody dynamic</td>
<td>BEM theory</td>
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<td>Alcyone</td>
<td>CRES and NTUA, Gr</td>
<td>FEM</td>
<td>Free wake panel method</td>
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<td>BhowC</td>
<td>Siemens</td>
<td>Co-rotating elements</td>
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<td>DUWEC5</td>
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<td>FAST</td>
<td>NREL and Oregon State University, US</td>
<td>Modal approach</td>
<td>BEM theory</td>
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<tr>
<td>FLEX5</td>
<td>Technical University of Denmark, DK</td>
<td>Modal approach</td>
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<td>FLEXLAST</td>
<td>Stork Product Engineering, SPE, NL</td>
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<td>GAROS</td>
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<td>Modal approach</td>
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<td>GAST</td>
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<td>BEM theory</td>
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<tr>
<td>GH Bladed</td>
<td>Garrad Hassan and Partners, Ltd. UK</td>
<td>Multibody Dynamic</td>
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<td>HAWC</td>
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<td>HAWC2</td>
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<td>PHATAS</td>
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<td>TURBU</td>
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<td>Teknikernøen AB, Swed</td>
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<td>YawDyn</td>
<td>University of Utah and NREL, US</td>
<td></td>
<td>BEM theory</td>
</tr>
</tbody>
</table>

Notes: NREL—National Renewable Energy Laboratory, US
Aeroelastic Code with Damage Progression Capabilities
Iso-geometric - TWB

Flowchart:
- Failure Criteria Hashin
- Load
- ISO-TWB Structural Model
- ABD
- Laminates
- Geometry
- $\sigma_j^{ii}$ (s,r, layers)

Logic:
- If not failure, continue
- If failure, update $n_i$
- $n_i = 0$
- $NF_{ii}(s, r, layer)$
- $\Delta n$ @ % new Damage Vol
- $n_{i+1} = n_i + \Delta n$
- Degradation Rules
- Materials
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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Kerop Janoyan, Co-Director CECET Blade Test Facility, Clarkson University, kerop@clarkson.edu
Constant Amplitude Progressive Failure Analysis (video)
Flow Structure Interaction and PFA

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

Flapwise displacement and azimuth position of the blade
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?

Based on FEM Model

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