Parametric modelling of large wind turbine blades

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(now at ¹Oxford Brookes University and ²SAMTECH Iberica)

SGEN-Wind 2, Educational Seminar, Strathclyde University, 23 September 2010
Structure

- Introduction
- Design aims / data inputs
- Materials / basic structure
- Blade modelling
- Blade loads (aerodynamics, aerofoils, ISO 61400-1)
- 5 MW (61 m) blade
- Full-scale blade testing

- Which are the best materials?
- What is the optimum lay-up?
- What is the best internal structure?
- What are the size limits – if any?
- What additional stresses do smart control devices generate in a blade?
- How should NDT measurements be interpreted?
Wind turbine blade design

Wind turbines are getting very large…

$$\phi = \text{Rotor Diameter}$$
Wind turbine blade design

Wind turbines are getting very large…

$\phi = \text{Rotor Diameter}$

- 50 kW $\phi 15m$ (1980)
- 100 kW $\phi 20m$ (1985)
- 500 kW $\phi 40m$ (1990)
- 600 kW $\phi 50m$ (1995)
- 2,000 kW $\phi 80m$ (2000)
- 5,000 kW $\phi 124m$ (2003)
- 8,000 - 12,000 kW $\phi 180m$ (2010)

Picture credit: EWEA
Wind turbine blade design

LM Glasfiber 61.5 m blade
…c.f. Boeing 747-400 wingspan 65 m
Wind turbine blade design
Wind turbine blade design

- Maximise energy yield
- Limit maximum power output
- Maximise material static and fatigue strength
- High blade stiffness
- Minimise overall rotor mass
- Avoid potential resonance conditions
- Lightning protection
- Radar interaction
Wind turbine blade design (2)

• Uni-axial materials data
• Multi-axial blade load conditions
• A wind turbine blade is a composite of composites
  – Current interest is concentrating on the adhesive connection between sub-structures
• Design standards
  – Material and structural safety factors
• Full scale blade certification test
  – Artificial load distribution / accelerated lifetime
=> Role for a comprehensive, parametric blade model
Materials selection and testing

- Low weight / high stiffness => fibre composites
  - Low cost
- Structural behaviour sensitive to:
  - Exact fibre lay-up
  - Manufacturing process
  - Joints
- Supergen Wind concentrating on fatigue behaviour
  - New materials (fibres, resins, fabrics)
  - Joints between different composites
  - Tests involving realistic design features
  - Tests incorporating realistic defects
Wind turbine blade structure

Option 1:
Main spar with sandwich skin

Option 2:
Spar cap with shear webs and blade skin

Figure after Ole Thybo Thomsen, Aalborg University
Wind turbine blade manufacture

• Manufacturing process
  – Varies with manufacturer
  – Basic material usually glass/epoxy
  – Typically based on composite prepreg technology or resin infusion process
  – Some manufacturers use wood/epoxy
  – Increasing use of carbon fibre
  – Foam/balsa core in shear webs and lightly loaded shells

• Loads
  – Flapwise bending carried by main spar or spar-caps
  – Edgewise bending carried by the blade skin shells
  – Flapwise shear loads carried by shear webs
Wind turbine blade failure modes

• Peak flapwise bending
  – Turbine (at standstill) experiences 50-year extreme gust
  – Most critical load for small, medium, and even quite large blades

• Local buckling
  – Aerofoil shells have very high chord and span to thickness ratios
  – Prone to “local” buckling - especially on compression (suction) surface
  – Behaviour sensitive to manufacturing faults and developing fatigue damage
  – Predominant failure mode
Wind turbine blade structure and testing

Flanges, web, bondlines

Sandwich

Blade root

Repair

Spar end detail

Figure after Denja Lekou, CRES, Greece
Parametric blade model: Design strategy

- Parametric processing tool for creation and running of the underlying FE model
- Suitable for sensitivity analyses, flexibility, documenting, re-usability
  - Python script front end for automation of the Abaqus FE package
  - Modular program
  - Realistic load application, including quasi-static aerodynamic loading
  - Ultimate strength & fatigue analysis
  - Developing dynamic implementation
Parametric blade model:
Geometry definition

=> parameter sweeps: e.g.

- tip deflection
- max stress

- d - shear web offset (mm)
Parametric blade model: Geometry definition
Parametric blade model:
Lay-up
Parametric blade model:
Variable mesh density...

... at the push of a button
Parametric blade model
Parametric blade model: 
Blade loads

- Gravity
- Centrifugal
- Aerodynamic
- (Inertial loads)
Blade loads – actuator disc

Bernoulli: \[ p_1 + \frac{1}{2} \rho V_1^2 = p_2 + \frac{1}{2} \rho V_2^2 \]
\[ p_3 + \frac{1}{2} \rho V_3^2 = p_4 + \frac{1}{2} \rho V_4^2 \]

Momentum: \[ T = m(V_1 - V_4) = \rho V_2 A(V_1 - V_4) \]

Force: \[ T = A \left( p_2 - p_3 \right) \]
Blade loads – actuator disc

Manipulate equations to get:

\[ V_2 = V_3 = \frac{1}{2}(V_1+V_4) \]

Axial flow induction factor: \( a \)

\[ V_2 = V_1(1-a) \]
\[ V_4 = V_1(1-2a) \]

Hence:

\[ T = 2 \rho A V_1^2 a(1-a) \]

Power:

\[ P = TV_2 = \frac{1}{2} \rho A V_1^3 4a(1-a)^2 \]

Power coefficient:

\[ C_p = 4a(1-a)^2 \]

Betz limit (\( a=1/3 \)):

\[ C_p = 16/27 = 0.593 \]

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Aerofoils

Angle of attack: \( \alpha \)
Relative wind velocity: \( u \)
Aerofoil plan area: \( A \)

Lift, drag coefficients: \( C_L, C_D \)

Lift = \( \frac{1}{2} \rho u^2 C_L A \)
Drag = \( \frac{1}{2} \rho u^2 C_D A \)

Pictures: Walt Musial, NREL
Blade-element momentum theory (BEM)

BEM fundamental assumption:
Force on a blade element = change of momentum of air passing through the annulus swept by the element

- 2D aerofoil characteristics: $C_L(\alpha)$, $C_D(\alpha)$
- Use BEM to evaluate $a$ and $a'$ at radial (spanwise) blade-elements and hence angles $\phi$ and $\alpha$
Blade-element momentum theory (BEM) + panel code

- 2D aerofoil characteristics: $C_L(\alpha)$, $C_D(\alpha)$
- BEM fundamental assumption:
  
  Force of a blade element = change of momentum of air passing through the annulus swept by the element

- Use BEM to evaluate $a$ and $a'$ at radial (spanwise) blade-elements and hence angles $\phi$ and $\alpha$
- Panel code (own or XFOIL) to calculate blade surface pressure coefficients and hence...
Parametric blade model: Fully distributed aerodynamic load
Example application – collective v. cyclic pitch control

3° cyclic: maximum flap load reduced by 8.4% while edge load is relatively unchanged (WARNING: quasi-static)
Wind turbine class:

<table>
<thead>
<tr>
<th>Wind turbine class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{ref}}$ (m/s)</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td>Values to be specified by designer</td>
</tr>
<tr>
<td>A</td>
<td>I_{\text{ref}} (-)</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>I_{\text{ref}} (-)</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>I_{\text{ref}} (-)</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Classes I-III do not attempt to include offshore conditions or tropical storms such as hurricanes, cyclones, or typhoons.

Wind conditions:

- **Normal wind conditions**
  - Wind speed distribution (Rayleigh)
  - Normal wind profile model (NWP)
  - Normal turbulence model (NTM)

- **Extreme wind conditions**
  - Extreme wind speed model (EWM)
  - Extreme operating gust (EOG)
  - Extreme turbulence model (ETM)
  - Extreme direction change (EDC)
  - Extreme coherent gust with direction change (ECD)
  - Extreme wind shear (EWS)

\[
P_R (V_{hub}) = 1 - \exp \left[ -\pi \left( \frac{V_{hub}}{2V_{ave}} \right)^2 \right]
\]

\[
V_{ave} = 0.2V_{ref}
\]

\[
V(z) = V_{hub} \left( \frac{z}{z_{hub}} \right)^\alpha 
\quad \text{where } \alpha = 0.2
\]

\[
\sigma_1 = I_{ref} (0.75V_{hub} + b) 
\quad \text{where } b = 5.6 m/s
\]
Load types:

• Gravitational and inertial
  – Gravity
  – Vibration
  – Rotation
  – Seismic activity

• Aerodynamic loads
  – Function of wind speed, turbulence, rotational speed, aerofoil shape, aeroelastic effects, etc

• Actuation loads
  – Torque control (from generator/inverter)
  – Yaw and pitch actuators
  – Mechanical braking

• Other loads
  – Wake loads
  – Impact loads
  – Icing

Type of analysis:
• Ultimate loads (U)
  – Ultimate strength
  – Critical deflection
  – Stability (buckling)
• Fatigue analysis (F)

Design situation:
• Normal (N)
• Abnormal = Fault (A)
• Transportation, installation, and maintenance (T)

External conditions:
• Normal
• Extreme

Design load cases:
1. Power production
2. Power production + fault occurrence
3. Start up
4. Normal shut down

Design load cases:
5. Emergency shutdown
6. Parked (standstill or idle)
7. Parked + fault condition
8. Transport, assembly, maintenance
For each relevant design load case:

<table>
<thead>
<tr>
<th>PSF for loads ($\gamma_f$)</th>
<th>1.35 (N)</th>
<th>Unfavourable loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 (A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 (T)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 (ALL)</td>
<td></td>
<td>Favourable loads</td>
</tr>
</tbody>
</table>

"Design" load

$$F_d = \gamma_f F_k \leq \frac{1}{\gamma_m \gamma_n} f_k$$

<table>
<thead>
<tr>
<th>Characteristic value of material property</th>
</tr>
</thead>
</table>

PSF for materials ($\gamma_m$)

- $\geq 1.1$ (ductile)
- $\geq 1.2$ (curved shell – buckling)
- $\geq 1.1$ (rupture)

PSF for consequence of failure ($\gamma_n$)

<table>
<thead>
<tr>
<th>Component class</th>
<th>Class 1 : 0.9</th>
<th>Class 2 : 1.0</th>
<th>Class 3 : 1.3</th>
</tr>
</thead>
</table>

Material type/load

- Ductile
- Curved shell – buckling
- Rupture

For each relevant design load case:
- Assess load spectrum
- Apply Miner’s damage rule

“Design” load

\[ F_d = \gamma_f F_k \leq \frac{1}{\gamma_m \gamma_n} f_k \]

Characteristic load

PSF for loads (\(\gamma_f\))
- 1.0

PSF for materials (\(\gamma_m\))
- \(\geq 1.5\) to 1.7
  - Material type/load
- For S-n curve based on 50% survivability and low or high coefficient of variation
- \(\geq 1.2\) (fibre composites where S-n curve based on 95% survivability)

PSF for consequence of failure (\(\gamma_n\))
- Class 1 : 1.0
- Class 2 : 1.15
- Class 3 : 1.3

Characteristic value of material property

Miner’s damage rule:

\[ D = \sum_i \frac{1}{N(S_i)} \]

Load range for \( i^{\text{th}} \) cycle

Discretised limit state relation for fatigue analysis:

\[ \sum_{j,k} \frac{n_{jk}}{N(\gamma S_k)} \leq 1 \]

\( n_{jk} \) is the expected number of lifetime load cases in the \( j^{\text{th}} \) wind speed and \( k^{\text{th}} \) load bin

\[ \gamma = \gamma_f \gamma_m \gamma_n \]

\( S_k \) is the centre value for the \( k^{\text{th}} \) load bin
5 MW (61 m) blade model

- Basic lay-up information
- Target mass and stiffness distributions
- Limitations of lay-up information
  - Overall mass
  - Discretisation of lay-up info
  - Required spar-cap stress profile?
- Lay-up modification
- Materials variation
- Static load case (aerodynamic load distribution)
- Fatigue lifetime
5 MW (61 m) blade model: Materials

<table>
<thead>
<tr>
<th>Material property</th>
<th>Baseline UD material</th>
<th>High fatigue strength material</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{1T}$ (GPa)</td>
<td>39.0</td>
<td>56.3</td>
</tr>
<tr>
<td>$E_{1C}$ (GPa)</td>
<td>38.9</td>
<td>-</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>$E_{2T}$ (GPa)</td>
<td>14.1</td>
<td>9.0</td>
</tr>
<tr>
<td>$E_{2C}$ (GPa)</td>
<td>14.997</td>
<td>-</td>
</tr>
<tr>
<td>$v_{21}$</td>
<td>0.95036E-01</td>
<td>0.95036E-01</td>
</tr>
<tr>
<td>$G_{12}$ (MPa)</td>
<td>4.24</td>
<td>4.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material property</th>
<th>Baseline UD material</th>
<th>High fatigue strength material</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_T$ (MPa)</td>
<td>776.5</td>
<td>1757</td>
</tr>
<tr>
<td>$X_C$ (MPa)</td>
<td>-521.8</td>
<td>-978</td>
</tr>
<tr>
<td>$Y_T$ (MPa)</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>$Y_C$ (MPa)</td>
<td>-165</td>
<td>165</td>
</tr>
<tr>
<td>$S$ (MPa)</td>
<td>56.1</td>
<td>135.4</td>
</tr>
</tbody>
</table>

**Fatigue**

<table>
<thead>
<tr>
<th>S-n curve at R=0.1</th>
<th>Baseline UD</th>
<th>High fatigue strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{max}} = S_0 \cdot N^{-\frac{1}{b}}$</td>
<td>$S_0 = 1176$</td>
<td>$S_0 = 1250$</td>
</tr>
<tr>
<td>$b = 9.74$</td>
<td>$b = 10.59$</td>
<td></td>
</tr>
</tbody>
</table>
5 MW (61 m) blade model: Spar-cap stress distribution (initial)
5 MW (61 m) blade model: Spar-cap stress distribution (adjusted)
5 MW (61 m) blade model: Spar-cap stress distribution (smoothed)
5 MW (61 m) blade model: Spar-cap stress distribution (lumped load)
5 MW (61 m) blade model: Static strength – skins and shear web

Choice of static failure criteria:
• Tsai-Wu
• Tsai-Hill
• Other (user specified)
5 MW (61 m) blade model: Static strength – skins and shear web

Choice of static failure criteria:
- Tsai-Wu
- Tsai-Hill
- Other (user specified)
5 MW (61 m) blade model: Static strength – bonding paste

Cohesive element model
• Normal stress component
• Shear stress component
• Linear up to characteristic value
• Material “softening”
5 MW (61 m) blade model: Fatigue strength estimation

- Complex loading
  - Stochastic / semi-deterministic (cyclic) loading
  - Biaxial (triaxial) stress state
- Fatigue characterisation
  - Predominantly uni-directional materials data
  - Uncertainty in how best to combine different stress cycles
    - R-ratio (minimum:maximum stress in a load cycle)
    - Combine into constant life diagram…

IEC 61400-1
5 MW (61 m) blade model: Fatigue strength estimation

Constant life diagram
- Linear Goodman diagram
5 MW (61 m) blade model: Fatigue strength estimation

Constant life diagram
- Multiple R-values diagram

\[ S_{\text{amp}} \quad (R = -1) \]

R = 0.1

\[ S_{\text{mean}} \]

UTS

UCS
5 MW (61 m) blade model: Fatigue strength estimation

Constant life diagram
- Multiple R-values diagram

\[ S_{\text{amp}} \ (R = -1) \]

- UCS
- \[ S_{\text{mean}} \]
- UTS

\[ R = 0.1 \]
5 MW (61 m) blade model: Fatigue strength estimation

Constant Life Diagram for MD material

Data: Optimat Blades
5 MW (61 m) blade model: Fatigue strength estimation

• Complex loading
  • Stochastic / semi-deterministic (cyclic) loading
  • Biaxial (triaxial) stress state

• Fatigue characterisation
  • Predominantly uni-directional materials data
  • Uncertainty in how best to combine different stress cycles
    • R-ratio (minimum:maximum stress in a load cycle)
    • Combine into constant life diagram…
    • …applies to a single material direction
    • How to deal with complex stress states?

IEC 61400-1

Biaxial stress ratio
5 MW (61 m) blade model: Biaxial stress ratio

Biaxial stress ratio is the ratio between the two largest magnitude principal stress components

...indicates regions of pure shear (-1), uniaxial stress (0), and full biaxial stress (1)

...allowing selection of appropriate material S-n data
5 MW (61 m) blade model: Fatigue strength estimation
5 MW (61 m) blade model: Fatigue lifetime

Min: $1.3 \times 10^9$

Baseline glass fibre

Uniaxial fatigue

$S = 1178.9 \cdot n^{-1.743}$

High performance glass fibre

Min: $1.6 \times 10^{10}$

$S = 1250.2 \cdot n^{-10.593}$
Full scale blade testing

• Static test (extreme load – representative of 1 in 50 years gust)
• Fatigue test (accelerated lifetime)
• Residual strength test
• Full-scale laboratory testing:
  – Design validation (typically strain gauges)
  – Test-bed for field condition monitoring techniques
Full scale blade testing
Thermoelastic stress analysis

Isotropic materials:
\[ \Delta T = -\frac{T}{\rho c_p} \alpha \Delta (\sigma_{11} + \sigma_{22}) \]

Orthotropic materials:
\[ \Delta T = -\frac{T}{\rho c_p} \left( \alpha_{11} \Delta \sigma_{11} + \alpha_{22} \Delta \sigma_{22} \right) \]
Full scale blade testing
Thermoelastic stress analysis

Blade test: blade with defects

Blade model: normal blade

Blade model: blade with defects
Condition monitoring: Acoustic emission

**AEGIS**

Acoustic Emission monitoring for Integrity of Structures

\[
\text{AEGIS} = \text{Shield of Zeus (impregnable defence)}
\]
AEGIS – static blade test procedure

Two part test:

- Mandatory certification loading to maximum test load (MTL) – typically a 10s “spike” load (representative of the 50 years’ maximum gust)

- AE examination loading (AEL) – trapezium-shaped load envelope including a 10 minute load-hold period, performed before and after any certification loading
AEGIS – fatigue blade test procedure

Four load stages:

- initial (low level) static AEL to operating load
- static AEL test to 10% above peak fatigue load at start and after every 500,000 cycles
- fast sinusoidal fatigue cycles to the peak fatigue load (AE hits recorded for the top 10% load of each cycle)
- after every 10,000 cycles, load application rate reduced to 10% giving 10 slower cycles
AEGIS : AE results - blade 7s static
AEGIS : AE results - blade 10f fatigue

AE sensors

AEGIS Blade 10 Loading: All fatigue data; Cycles vs. x position; legend = Log(Energy)atto-Joules

Failure at 2.05 m after 3961283 cycles

1.32 to 9.42 kN

1.02 to 5.42 kN
SUPERGEN Wind 1 - Achievements

- Flexible, parametric blade model for assessment of alternative materials
- Simple failure model in blade skin and developing damage model in bonding paste implemented
- Fatigue methodology under development
- Initial results also available for application to full-scale blade testing, control of smart blades and interpretation of condition monitoring data
- Supergen Wind 2 work planned on dynamic loading – operation in wakes from upstream turbines & “smart” blade devices
SUPERGEN Wind 2

- Further develop turbine wake interaction model (IC)
- Develop three-blade reduced degree of freedom rotor FE model to incorporate aero-elastic interaction (RAL)
- Link to Phase I work using sub-structures
- Assess new materials & construction techniques
- Assess control effects of aerodynamic control devices
Conclusions: Blade design

• Wind turbine blade design is complex and underpinned by
  – Fundamental materials data
  – Full-scale structural testing
  – Improved modelling capability

• Future requirements:
  – New materials
  – Smart control of blade and other machine loads
  – Improved understanding of fatigue and damage processes
  – On-line (blade) condition monitoring
Acknowledgements

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SUPERGEN Wind Energy Technologies Consortium

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