Fatigue Modeling of Large Composite Wind Turbine Blades

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Motivation

Fatigue modeling of large composite wind turbine blades
Outline

• Deterministic fatigue approaches
  ▪ Uniaxial
  ▪ Multi-axial

• Probabilistic fatigue approaches
  ▪ Uniaxial
  ▪ Multi-axial

• Conclusions and future work
Deterministic and uniaxial approach

Based on **IEC 61400-1** standard and **DNV GL** certification and design guidelines

- **Design Load Cases for fatigue:**
  - **DLC 1.2:** Power production (NTM)
  - **DLC 2.4:** Power production plus occurrence of fault (NTM)
  - **DLC 3.1:** Start up (NWP)
  - **DLC 4.1:** Normal shut down (NWP)
  - **DLC 6.4:** Parked (NTM)

- Design lifetime: **20 years**
- **10 min** average wind speed simulations
- No. seeds: **15**
Current standard method

Stress time series calculation

Cycle counting

Constant Life Diagrams

Fatigue Failure Criteria

Damage summation

Rainflow cycle counting

\((n_1, \sigma_{m,1}, \sigma_{a,1})\)

\((n_3, \sigma_{m,3}, \sigma_{a,3})\)

\((n, \sigma_{m,j}, \sigma_{a,k})\)

Goodman diagrams (Linear)

Uniaxial

\(\sigma_1(t)\)

Uniaxial

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Implemented cross section fatigue tool

HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation)

BECAS (BEam Cross section Analysis Software)

Geometry and layup
Material properties
Aeroelastic loads

Stress time series calculation
Cycle counting
Constant Life Diagrams
Fatigue Failure Criteria
Damage summation

HAWC2
BECAS
Study case: NREL 5 MW RWT spar caps

Span: 10.5 m  
DLC 1.2: Power production (NTM)  
Wind direction: 0 degrees  
No. seeds: 6  
Lifetime: 20 years

Material properties of Glass (UD) were taken from OptiDAT database

A. Suction side spar cap
B. Pressure side spar cap

Glass(UD)
Cumulative damage at spar caps

A. Suction side spar cap

B. Pressure side spar cap

Front shear web

Rear shear web

Diagram showing cumulative damage ($D$) at spar caps for suction and pressure sides, with color intensity indicating the level of damage.
Deterministic and multi-axial approach

Rainflow cycle counting

\((n_1, \sigma_{m,1}, \sigma_{a,1})\)

\((n_3, \sigma_{m,3}, \sigma_{a,3})\)

\(n\)

Multi-axial fatigue criterion

Stress time series calculation

Cycle counting

CLD

Fatigue Failure Criteria

Damage summation

Multi-axial

\(\sigma_1(t)\)

\(\sigma_2(t)\)

\(\sigma_6(t)\)

Piecewise linear

\(n, \sigma_{m,j}, \sigma_{a,k}\)

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Palmgren-Miner rule (Linear)

(20 years)
Stress time series for mesh element No 455 obtained by using BECAS. 10 min of simulation for a wind speed of 13 m/s and DLC 1.2
Constant life diagrams

Longitudinal direction

Transverse direction

Glass(UD)

In-plane shear

Experimental data from OptiDAT Database
Fatigue failure criteria

Failure Tensor Polynomial in Fatigue (FTPT)

\[
\frac{\sigma_{1amp}^2}{X^2(N)} + \frac{\sigma_{2amp}^2}{Y^2(N)} - \frac{\sigma_{1amp}\sigma_{2amp}}{X(N)Y(N)} + \frac{\sigma_{6amp}^2}{S^2(N)} - 1 = 0 \quad \rightarrow \quad N
\]

Where \(X(N), Y(N)\) and \(S(N)\) denote the corresponding S-N curves

For correlated \(\sigma_{1amp}, \sigma_{2amp}\) and \(\sigma_{6amp}\) a linear relationship can be defined:

\[
\sigma_{jamp} = \rho_{\sigma_1 \sigma_j} \left( \frac{\sigma_{1amp}}{Std_{\sigma_1}} \right) * Std_{\sigma_j}
\]

\[
\sigma_{jmean} = \mu_{\sigma_j} + \rho_{\sigma_1 \sigma_j} \left( \frac{\sigma_{1amp} - \mu_{\sigma_1}}{Std_{\sigma_1}} \right) * Std_{\sigma_j} \quad j = 2 \text{ or } 6
\]

According to Gardoni & Der Kiureghian

\[
\left| \rho_{\sigma_1 \sigma_j} \right| \geq 0.7
\]
Correlation between $\sigma_1$ and $\sigma_2$

Correlation factors $\rho_{\sigma_1\sigma_2}$ from 10-min simulations for wind speed of 13 m/s and 25 m/s.

$\rho_{\sigma_1\sigma_2} = -1$

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Re-estimated $\sigma_2$

Wind speed of 13 m/s

Wind speed of 25 m/s

Re-estimated by

$$\sigma_2 = \mu_2 + \rho_1 \sigma_1 \sigma_2 \left( \frac{\sigma_1 - \mu_1}{\text{Std}_{\sigma_1}} \right) * \text{Std}_{\sigma_2}$$
Correlation between $\sigma_1$ and $\sigma_6$

Correlation factors $\rho_{\sigma_1\sigma_6}$ from 10-min simulations for wind speed of 13 m/s and 25 m/s:

- $\rho_{\sigma_1\sigma_6} = -0.9$ for 13 m/s
- $\rho_{\sigma_1\sigma_6} = -0.6$ for 25 m/s
Re-estimated $\sigma_6$

Wind speed of 13 m/s

Wind speed of 25 m/s

Re-estimated by

\[
\sigma_6 = \mu_6 + \rho \sigma_1 \sigma_6 \left( \frac{\sigma_1 - \mu_1}{\text{Std} \sigma_1} \right) * \text{Std} \sigma_6
\]
Cumulative damage at pressure side spar cap

A. Multi-axial approach

B. Uniaxial approach

- Results follow the trends found by Philippidis_Vassilopoulos_IJF_2002
- Underestimation of the cumulative damage when transverse and in-plane share stresses are neglected
- Possible overestimation of the cumulative damage when multi-axial criterion is applied
Cumulative damage at suction side spar cap

A. Multi-axial approach

B. Uniaxial approach

- Results follow the trends found by Philippidis_Vassilopoulos_IJF_2002
- Underestimation of the cumulative damage when transverse and in-plane share stresses are neglected
- Possible overestimation of the cumulative damage when multi-axial criterion is applied
Probabilistic approaches

Geometry and layup → Stress time series calculation → Cycle counting → CLD → Fatigue Failure Criteria → Damage summation → Limit state equation → Probability of failure

X: uncertainty variables

X_{str}

X_{RFC}

X_{L}

X_{PMR}
Limit state equation

\[ g(X) = D_{\text{failure}} - D(X) \quad \rightarrow \quad g(X) = X_{\text{PMR}} - X_L^m X_{\text{str}}^m X_{\text{RFC}}^m D(X) \]

Where \( D(X) \) is the cumulative damage, \( X_L = X_{\text{load}} X_{\text{st}} X_{\text{exp}} X_{\text{aero}} X_{\text{dyn}} X_{\text{sim}} X_{\text{geom}} \) and \( m = 10 \)

**Reliability method:** Monte Carlo (sample size of 100000) to estimate \( \beta \) index values and \( P_f = \Phi(\beta) \)


<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Distribution</th>
<th>((\mu, \sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_{\text{load}} )</td>
<td>Load carrying capacity</td>
<td>Deterministic</td>
<td>(1.00; 0.00)</td>
</tr>
<tr>
<td>( X_{\text{st}} )</td>
<td>Limited wind data</td>
<td>Lognormal</td>
<td>(1.00; 0.05)</td>
</tr>
<tr>
<td>( X_{\text{exp}} )</td>
<td>Exposure</td>
<td>Lognormal</td>
<td>(1.00; 0.10)</td>
</tr>
<tr>
<td>( X_{\text{aero}} )</td>
<td>Airfoil coefficients</td>
<td>Gumbel</td>
<td>(1.00; 0.10)</td>
</tr>
<tr>
<td>( X_{\text{dyn}} )</td>
<td>Dynamics</td>
<td>Lognormal</td>
<td>(1.00; 0.05)</td>
</tr>
<tr>
<td>( X_{\text{sim}} )</td>
<td>Simulation</td>
<td>Normal</td>
<td>(1.00; 0.05)</td>
</tr>
<tr>
<td>( X_{\text{geom}} )</td>
<td>Normal</td>
<td>Normal</td>
<td>(1.00; 0.03)</td>
</tr>
<tr>
<td>( X_{\text{str}} )</td>
<td>Stress analysis</td>
<td>Lognorm</td>
<td>(1.00; 0.05)</td>
</tr>
<tr>
<td>( X_{\text{RFC}} )</td>
<td>Rainflow count</td>
<td>Lognorm</td>
<td>(1.00; 0.02)</td>
</tr>
<tr>
<td>( X_{\text{PMR}} )</td>
<td>Palmgren-Miner rule</td>
<td>Lognorm</td>
<td>(0.33; 0.21)</td>
</tr>
</tbody>
</table>
Probability of failure at pressure side spar cap

- Results consistent with deterministic ones
- Underestimation of probability of failure when transverse and in-plane share stresses are neglected
- Possible overestimation of probability of failure when multi-axial criterion is applied

A. Multi-axial approach

B. Uniaxial approach
Probability of failure at suction side spar cap

- Results consistent with deterministic ones
- Underestimation of probability of failure when transverse and in-plane shear stresses are neglected
- Possible overestimation of probability of failure when multi-axial criterion is applied
Effects of model uncertainties on estimated probability of failure

A. Multi-axial (Model uncertainties)

B. Multi-axial (Not model uncertainties)

- High effects of model uncertainties on the probability of failure
Conclusions

• The fatigue response of the spar caps was analyzed by implementing both deterministic and probabilistic approaches. For both cases, uniaxial and multi-axial fatigue approaches were implemented.

• Correlation factors between axial stresses and both transverse and in-plane shear stresses of the blade were used to apply the fatigue multi-axial criterion.

• The cumulative damage (uniaxial case) and the probability of failure (multi-axial case) were underestimated by applying uniaxial fatigue approaches and possibly overestimated by applying multi-axial approaches.

• It was showed how the uncertainty variables have high effects on the probability of failure.
Current work

\[ X_{GEOM} \]
Geometry and layup

\[ X_{elas}; X_{stren}; X_{SN} \]
Material properties

\[ X_L \]
Aeroelastic loads

\[ X_{str} \]
Stress time series calculation

\[ X_{RFC} \]
Cycle counting

\[ X_{CLD} \]
CLD

\[ X_{FFC} \]
Fatigue Failure Criteria

\[ X_{PMR} \]
Damage summation

\[ X \]
uncertainty variables

Statistical, physical and model uncertainties

Limit state equation

Probability of failure

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DTU Wind Energy, Technical University of Denmark
Thanks!