Development of thermal residual stresses during manufacture of wind turbine blades

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Motivation

Failures in field at trailing edge (1)

Wetzel, 2009

Baby, 2018

Westegaard, 2013
Motivation

Failures in field at trailing edge (2)
Motivation

Failures in field at trailing edge (3)
Methods
Thermal Analysis of Cooling after Curing Cycle

Adhesive Application

- Blade Shells Assembled

Demolding

- 70 °C for 5 hours
- 23 °C
Methods
Analytical Classical Laminated Plate Theory (CLT)

(a)  
\[ \alpha_{TSS} \Delta T \]
\[ \alpha_{Ta} \Delta T \]
\[ \alpha_{TPS} \Delta T \]
\[ -\sigma_z^R + \sigma_z^R \]

(b)  
\[ \alpha_{Tb} \Delta T \]
Methods

Finite Element Plate Models

n-sliced solid

3-sliced layered solid

1-sliced layered solid

Homogeneous SOLID186

Layered SOLID186

Layered SOLID186

Shell

Solid/shell MPC

Solid/shell share

SHELL281

SHELL281

SHELL281

Homogeneous SOLID186

Homogeneous SOLID186

Homogeneous SOLID186
Plate Benchmark
Use case: 34 m blade design

- 1-sliced layered solid suffers from shear locking
- Solid/shell share underestimates the reference
- Analytical model neglects plate bending
Methods
Finite Element Blade Model
Results - Blade Distortion (1)

Use case: 34 m blade design

- Tip swepted by 78 mm toward trailing-edge
- Tip twisted by -0.2° toward feather
- Cross-section deformed
Results - Blade Distortion (2)

Use case: 34 m blade design

- Target shape
- Distorted shape (scale factor = 5)

Relative displacement $\delta$ in mm

Relative span-wise position $z$
Results - Blade Stress (1)

Use case: 34 m blade design

![Blade Stress Diagram](image)

**Graph:**
- Residual stress $\sigma_{z}^{R}$, Blade
- Residual stress $\sigma_{s}^{R}$, Blade
- Residual stress $\tau_{st}^{R}$, Blade
- Residual stress $\sigma_{z}$
- Residual stress $\sigma_{s}$
- Residual stress $\sigma_{t}$
- Residual stress $\tau_{zt}$

**Axes:**
- Y-axis: Residual stress $\sigma_{z}^{R}$, $\sigma_{s}^{R}$, $\tau_{st}^{R}$ in MPa
- X-axis: Relative span-wise position $z$

**Legend:**
- Solid/shell share (plate)
- Analytical
- Solid/shell share (plate)
- Analytical
- Solid/shell share (plate)
- $\sigma_{z}^{R}$, Blade

**Software:**
- SHELL281
- Homogeneous SOLID186

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Results - Blade Stress (2)

Use case: 34 m blade design

- Equivalent stress according to Beltrami
- Analytical model captured stress trend of full 3D FE model
- Analytical model did not take into account effects stemming from whole blade structure
Conclusions and Future Work

- Analytical CLT model applicable for predicting thermal residual stress trend as observed in full 3D FE model
- Effects stemming from whole blade structure not taken into account
- “Solid/shell share” technique as implemented in full FE model underestimated the stress level of a higher fidelity model
- “Solid/shell MPC” technique seems to be implemented most simply into a state-of-the-art FE blade shell model followed by the “3-sliced layered solid” technique
Thank you for your attention!
Any questions?
Stress components
At rel. blade length $z = 0.5$
Stress components

At rel. blade length $z = 0.5$

- Residual stress $\sigma^R_s$ in MPa

![Graph showing stress components and bond line width](image)
Stress components
At rel. blade length $z = 0.5$
Stress components

At rel. blade length \( z = 0.5 \)

\[
\sigma_{e}^{R} = \left\{ \left( \sigma_{z}^{R} \right)^{2} + \left( \sigma_{s}^{R} \right)^{2} + \left( \sigma_{t}^{R} \right)^{2} - 2\nu \left( \sigma_{z}^{R} \sigma_{s}^{R} + \sigma_{s}^{R} \sigma_{t}^{R} + \sigma_{t}^{R} \sigma_{z}^{R} \right) \right\}^{1/2}
+ 2 \left( 1 + \nu \right) \left[ \left( \tau_{zs}^{R} \right)^{2} + \left( \tau_{st}^{R} \right)^{2} + \left( \tau_{zt}^{R} \right)^{2} \right]^{1/2}
\]