Structural design and analysis of a 10 MW wind turbine blade

Deep Sea Offshore Wind R&D Seminar

Royal Garden Hotel, Trondheim, Norway
19 January, 2012

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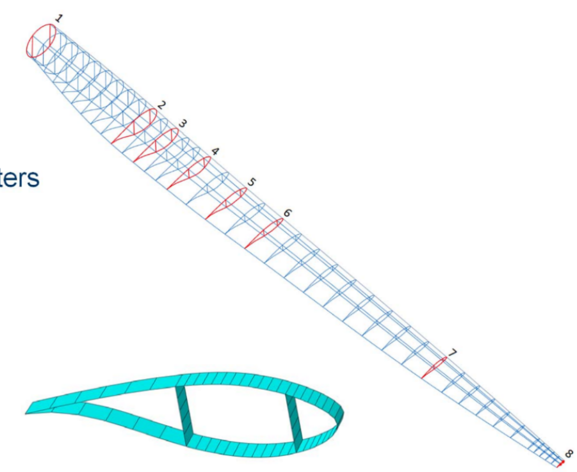

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Motivation

- Little information publically available on blade structure
  - Significant lack of
    - Composite layups
    - Buckling studies
- Many existing studies on blade structure use simplified loading conditions
  - Omit gravity and centrifugal loads
  - Simplified wind (lift) loads, no drag or torsional loads
- Airfoil skin is often not included in FE studies
  - Has little effect on bending stiffness
  - Very significant for buckling studies

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Objective

To specify the structural aspects of a 70 m blade to be used as a reference case for future research projects

- Designed with respect to industry standard failure criteria for composites
- Select appropriate materials
- Determine composite layup
  - Ply thickness, number, stacking sequence
  - Fiber orientations
  - Ply drop locations
- Investigate optimization techniques
  - Composite sandwich structures
  - Adaptive blade: bend-twist coupling

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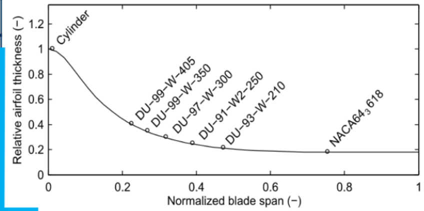
10 MW Turbine and Blade Parameters

► Defined in [Frøyd and Dahlhaug. Rotor design for a 10 MW offshore wind turbine. ISOP, Maui, USA, 2011)

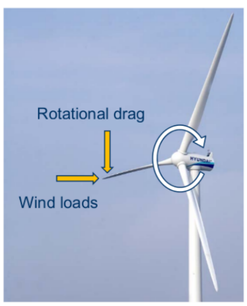
Turbine specifications parameters	
Rated power	10 MW
Rotor configuration	3 blades, upwind
Design, rated wind speed	13, ~15-16 m/s
Design, Optimal TSR	7.3, 7.64
Max. tip velocity	90 m/s
Tilt & coning angles	$\theta_{shaft} = 5^o$, $\theta_{cone} = 2^o$
Control	Variable speed & pitch
Rotor diameter	141 m
Blade length	68 m + 2.47 m inside root
Twist angles	0 ° - 13.7 °
Max tip deflection (m)	8.5 (rotating), 11.5 (parked)
Natural freq. of blade	above 0.671 Hz

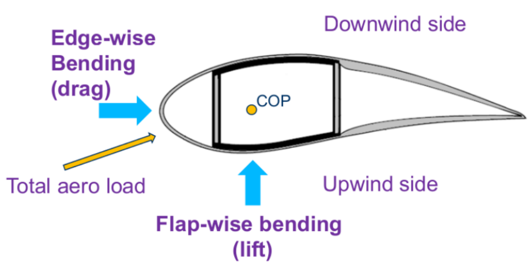


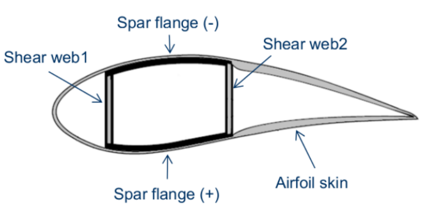
Short blades with
Large wind loads gives
High power output

HAWC2 analyses performed to give aerodynamic loads on blades

Blade structural design

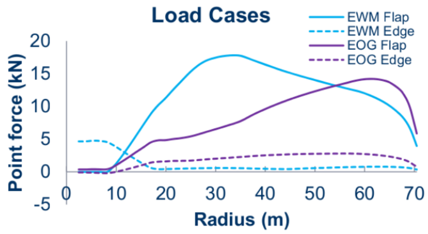






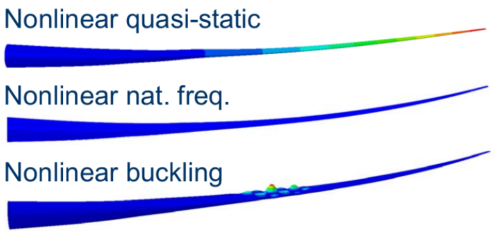
Component	Structural function
Airfoil skin	Edge-wise, torsional stiffness
Spar flanges	Flap-wise bending stiffness Buckling resistance
Shear webs	Shear stiffness

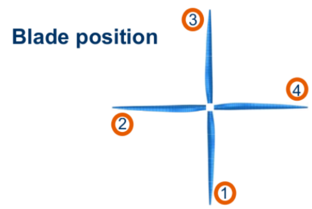
Simulations Performed in Abaqus



	EWM	EOG
Wind speed	70 m/s	19.3 m/s
Omega	0 rad/s	1.28 rad/s
Blade pitch	90º	0º
Yaw error	15º	0º

EWM (extreme wind speed model)
EOG (extreme operating gust)





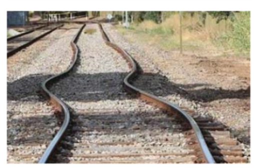
What is buckling?

- Instability failure due to compressive forces
  - Buckling failure occurs **before** the ultimate compressive stress/strain of the material
  - Nonlinear phenomenon
  - Buckling occurs at a critical load (force) at which the structure fails:

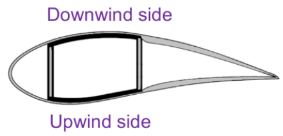
$$F_{crit} \propto \frac{1}{length^2}$$

Compare critical load for different rod lengths
(Constant cross-section and stiffness)

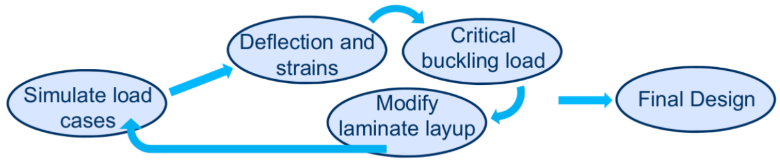
Rod length	Normalized critical load
50 meters	100%
60 meters	69%
70 meters	51%

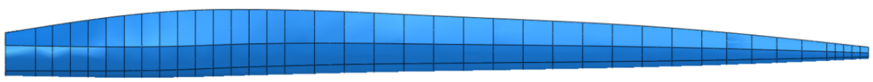


Design strategy: composite layup



- Iterative procedure
  - Blade split into 38 sections
  - One ply added to one section at a time
  - Symmetric and balanced layup
  - Equivalent layups on upwind and downwind sides
  - No more than 2 plies (4 mm) could start or stop at any section

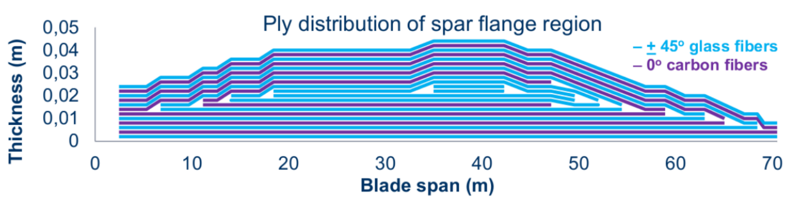




Spar flange layup

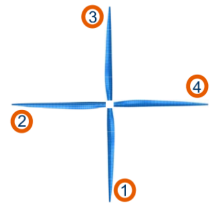
- Bending stiffness (flap-wise)
  - Carbon fiber plies stacked until strain failure and deflection criteria avoided
- Buckling resistance
  - $\pm$ 45° glass fiber plies added until critical load was > design load * SF
- *Aerodynamic shell and shear web layups presented in the paper*

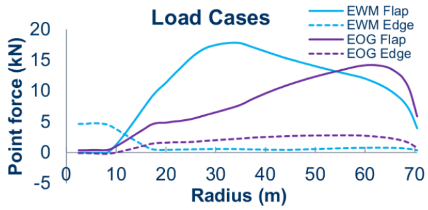
Material	E_{xx}	E_{yy}	G_{xy}	υ_{xy}	ρ	Thickness	Wt % of spar flange
0° Carbon	139 GPa	9 GPa	5.5 GPa	0.32	1560 kg/m3	2.0 mm	38.9 %
0° Glass	41 GPa	9 GPa	4.1 GPa	0.30	1890 kg/m3	1.0 mm	61.1%



Simulation results

Load case	Result	Position 1	Pos. 2	Pos. 3	Pos. 4
EOG	Tip flap def. (m)	5.052	5.072	**5.120**	5.115
	Max strain (%)	0.198	0.270	0.194	0.166
	Min strain (-%)	0.167	**0.277**	0.170	0.169
	Crit. buckling	2.005	1.898	1.666	1.872
EWM	Tip flap def. (m)	4.723	--NA--	4.795	--NA--
	Max strain (%)	0.181	--NA--	0.176	--NA--
	Min strain (-%)	0.154	--NA--	0.159	--NA--
	Crit. buckling	1.751	--NA--	**1.659**	--NA--

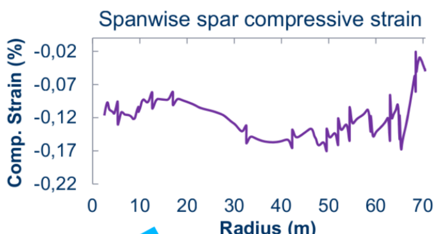


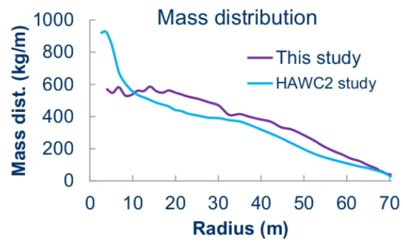


- EOG, Pos. 3 → Maximum tip deflection
- EWM, Pos. 3 → Critical buckling load
- EOG, Pos. 2 → minimum edgewise strain

- Critical buckling load drops by 26% in absence of airfoil skin

Simulation results

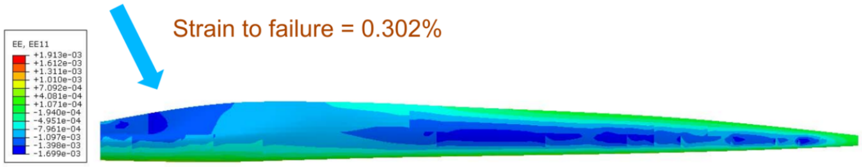




- This study: root connection not included
- HAWC2 study: buckling not included

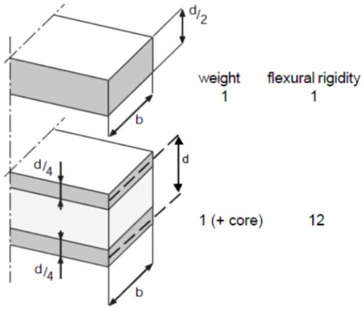
Strain during EOG, pos. 3

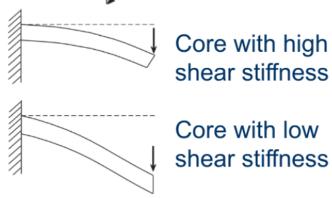
Strain to failure = 0.302%



Optimization study #1: Sandwich structure

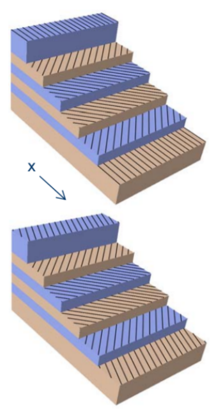
- ▶ Background
  - Increase structural performance with a minimal weight gain
  - 2 stiff skins separated by a lightweight core material
    - (Composite) skins provide bending stiffness
    - Core provides shear stiffness
- ▶ Optimization study
  - Implement 30 mm of core material in spar flanges
    - Decrease in bending stiffness
    - Increase in critical buckling load
    - Small increase in weight





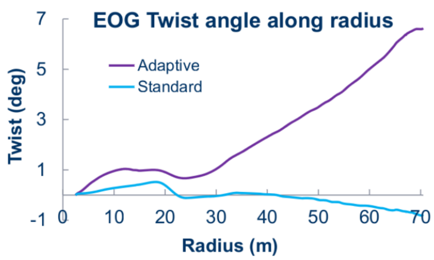
Optimization study #2: Adaptive blade

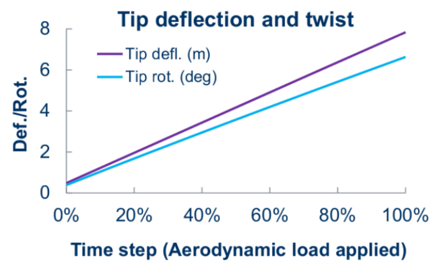
- ▶ Background
  - Ability of a blade to adapt to changes in loading conditions
    - Improved efficiency
    - Longer fatigue life
    - Reduce magnitude of high load conditions, ex. EOG
  - Composite materials can exhibit bend-twist coupling due to unbalanced layup
- ▶ Optimization study
  - Rotate all 0º carbon fibers by 20º
    - Twist induced towards feather (load reduction)
    - Decrease in flap-wise bending stiffness
    - Zero change in mass



Results of optimization studies

Optimization studies compared with standard blade results						
Optimization study	Tip flap def.	Min Strain	Crit. buckling load	Total mass	EOG Tip twist	EOG Nat. freq
Sandwich	5.40 m 5.5%	-0.204% 5.4%	2.27 **36.8%**	26086 kg **4.3%**	-1.0° 31.2%	0.706 hz -3.9%
Adaptive	**7.94 m** 55.0%	-0.259% 52.3%	1.68 0.9%	24935 kg 0.0%	**6.6°** -853.8%	**0.583 hz** -20.6%





Future studies

- ► Is the blade too stiff?
  - 8.5 m tip deflection allowed, but only 5.1 m achieved
- ► Fatigue
  - Edgewise
  - Flapwise
- ► Dynamic (wind gust) studies
  - Initial studies suggested no issues
- ► Bend-twist coupling
  - What does 6.6° twist mean for the turbine power output?
  - Is there load reduction and can it lessen requirements elsewhere in the turbine?

Conclusions

- Structural components of a 70 m blade were designed
  - Materials
  - Composite layups
- The blade was designed to withstand EOG and EWM load conditions
  - Tip deflection
  - Material strains
  - Critical buckling load
  - Natural frequency
- Optimization studies were performed and showed potential for further blade optimization
  - Sandwich structures: 36.8% increase in critical buckling load with 4.3% increase in mass
  - Bend-twist coupled blade: 6.6º of tip twist achieved during EOG

Questions

Thank you for your attention!

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