On Innovative Concepts of Wind Turbine Blade Design

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Risø National Laboratory for Sustainable Energy,
Technical University of Denmark

Outline

- Motivation

- Overview of failure modes which are expected to be design driven for future blades

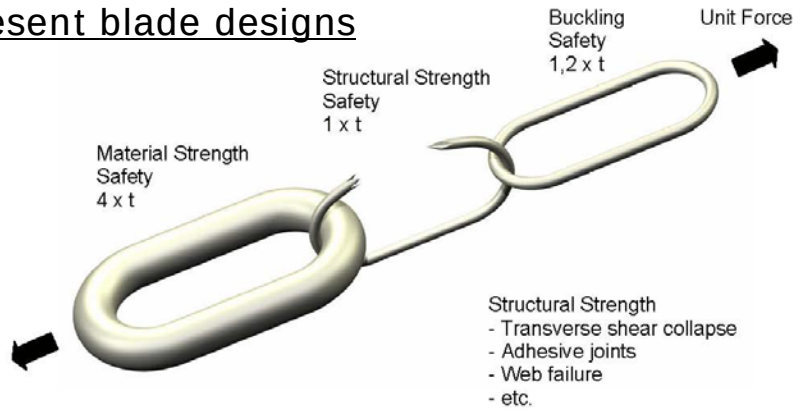
- New structural solutions preventing these failure modes

- An example on an on going research project where a blade is design and manufactured with some of these solutions

- Problems which must be addressed if a new light weight blade is installed in a WT

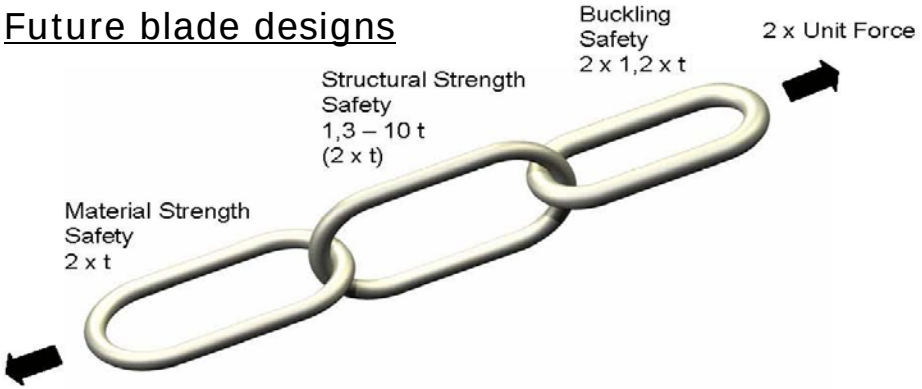
Motivation

Present blade designs



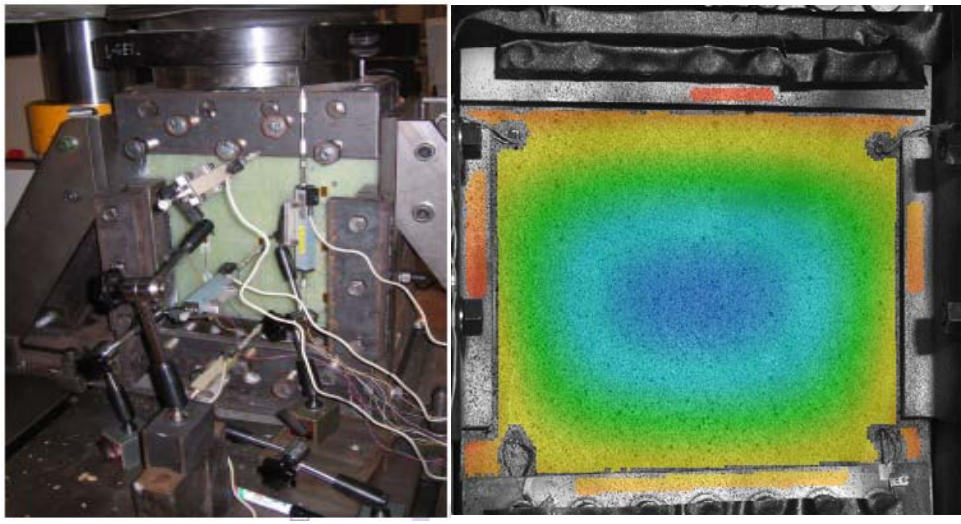
Structural strength seems to be the weak point for many blade designs

Future blade designs

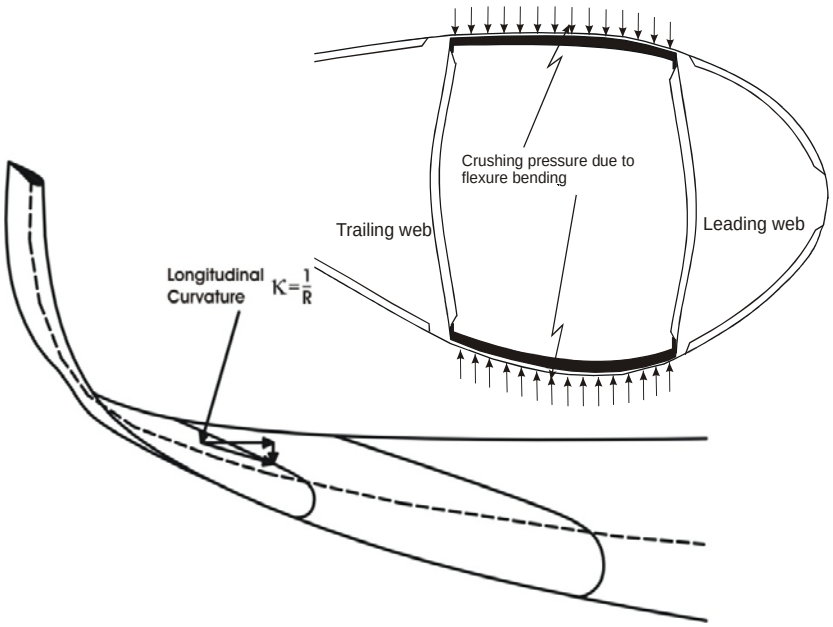


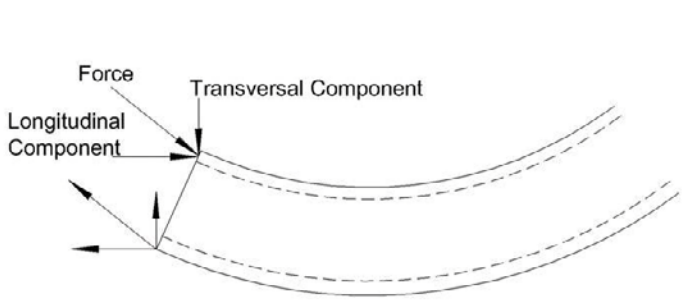
Goal: To find a better balance between structural strength collapse and material failure

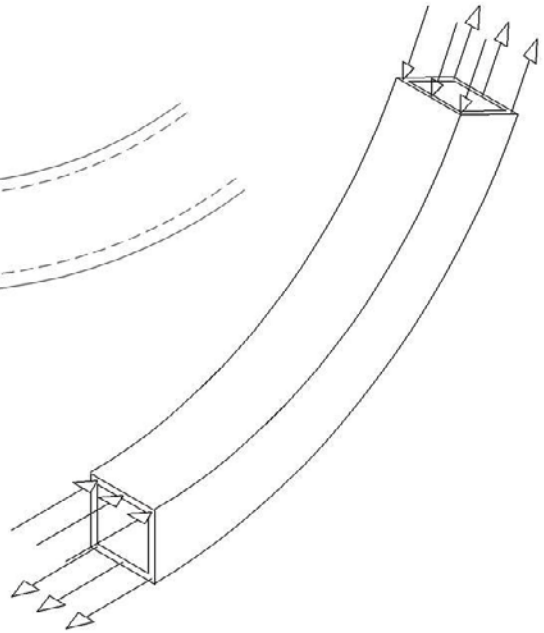
- In full-scale test 5000μS can be obtained before ultimate collapse
- In panel test of panels with same quality as the blade 15-30000μS is obtained before failure
- Conclusion: Compressive failure (static) of the material does not seem to be critical



Non-linear phenoma becomes more critical with flexible blades



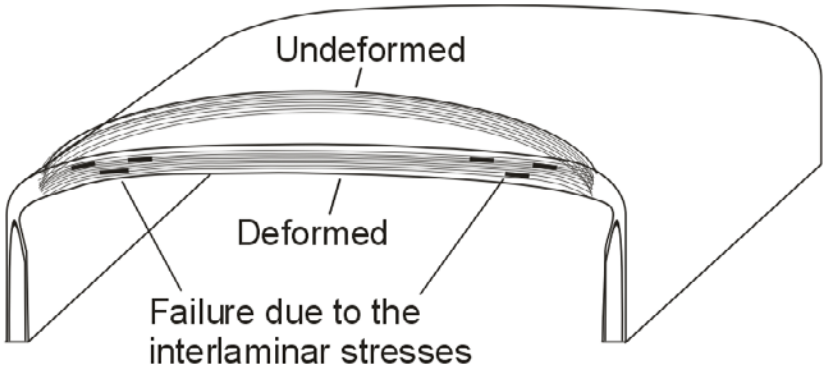


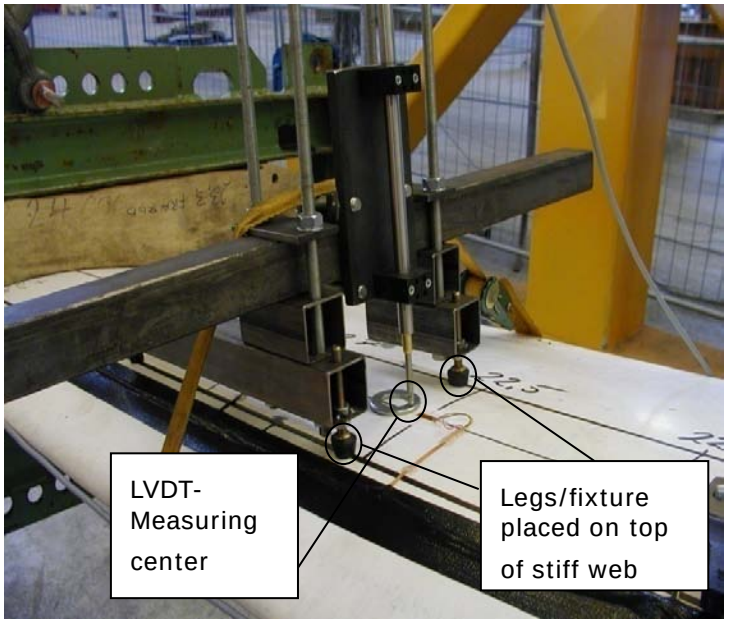


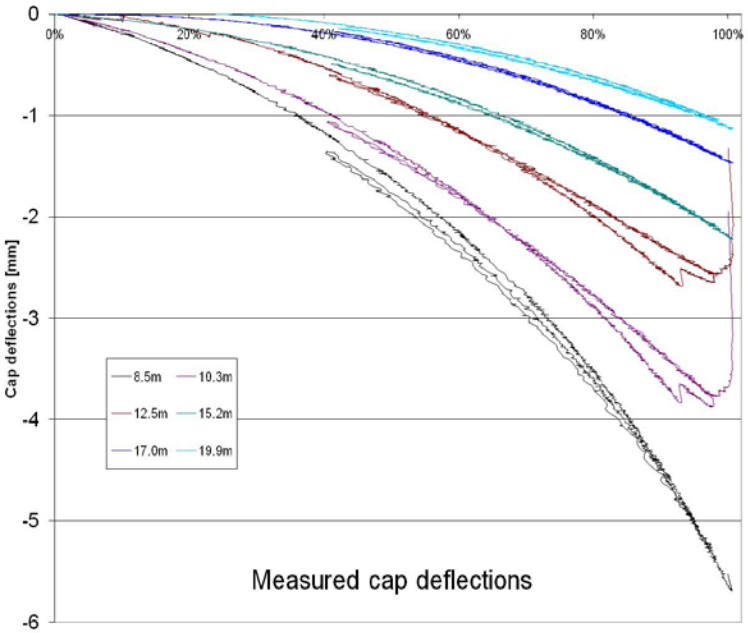
- Collapse appears when the blade, at the same time, is exposed to flapvise load, which gives a large “crushing pressure”

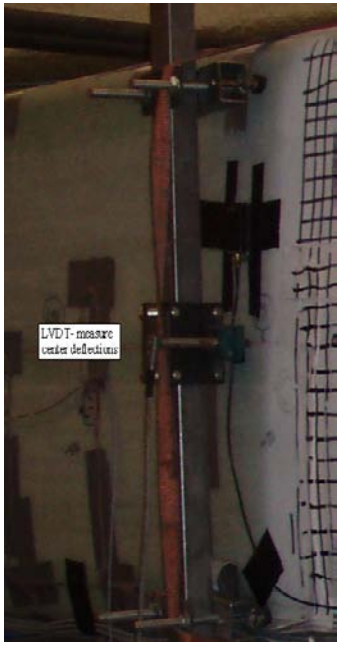
- “Crushing pressure” rises in the second power with the longitudinal curvature and when it is expected that the blades will be significantly more flexible in the future, such problem will be of increasingly importance

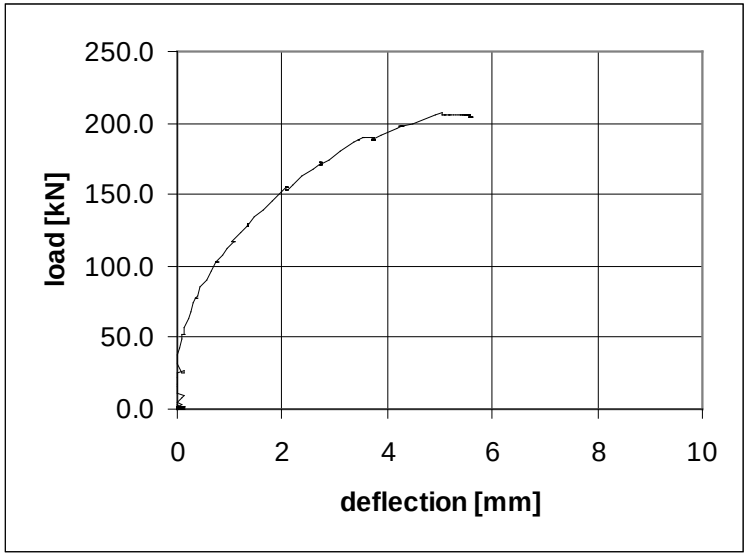
Interlaminar failures in the load carrying laminate



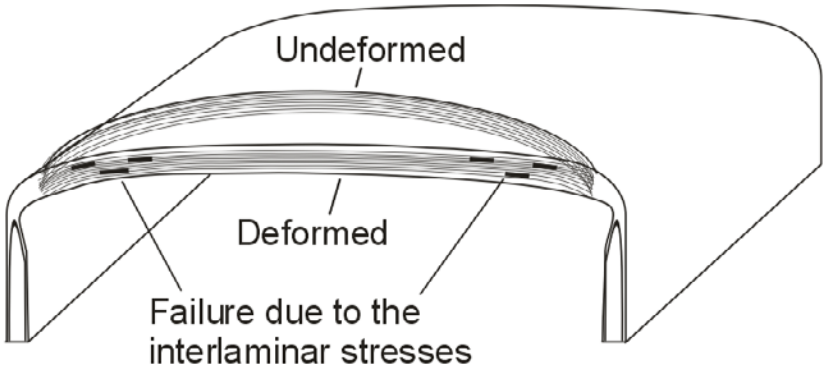


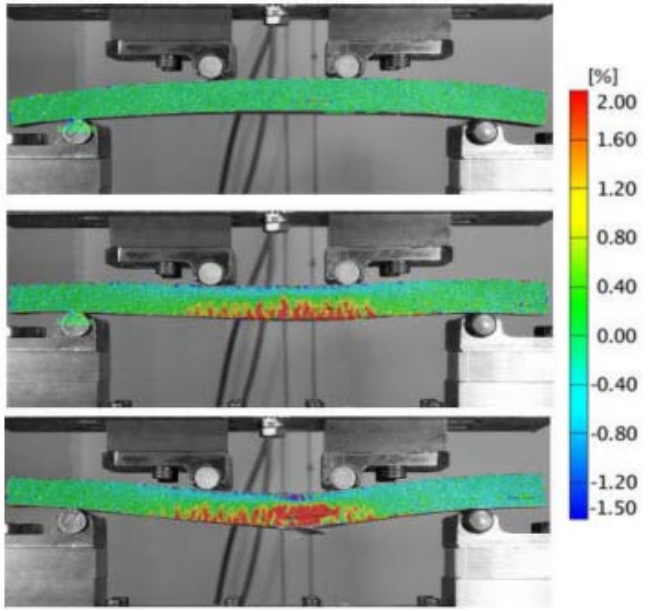


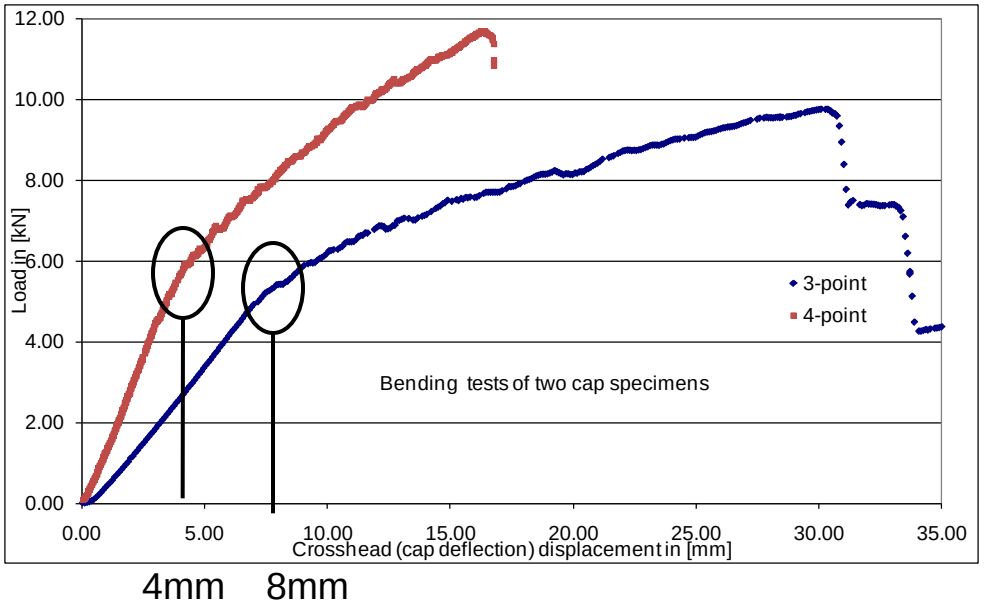




Interlaminar failures in the load carrying laminate





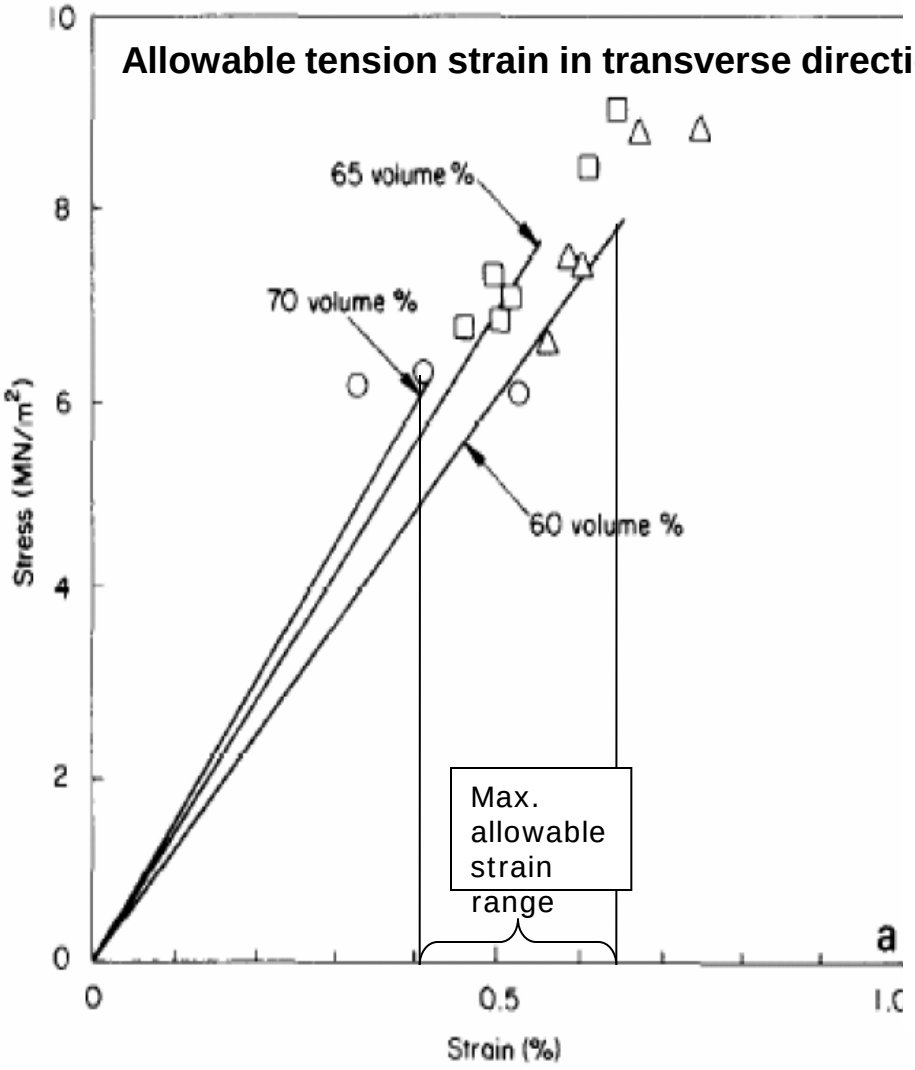


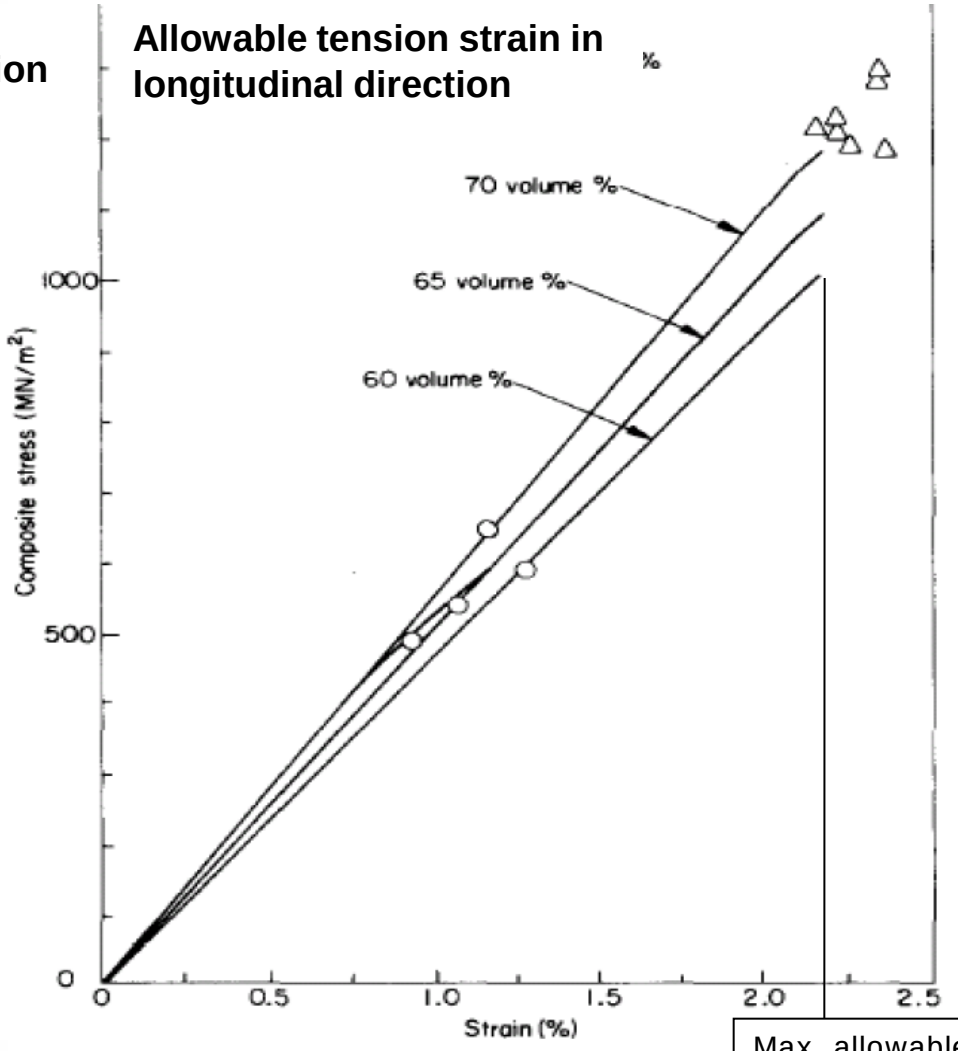
4mm 8mm

3- /4-point bending tests of SSP cap specimens were performed at Imperial College – Department of Mechanical Engineering.

The bending tests lead to initial interlaminar failure after 8mm and 4mm deflections in the 3 and 4-point bending tests.

Max strain in unidirectional glass fiber laminate

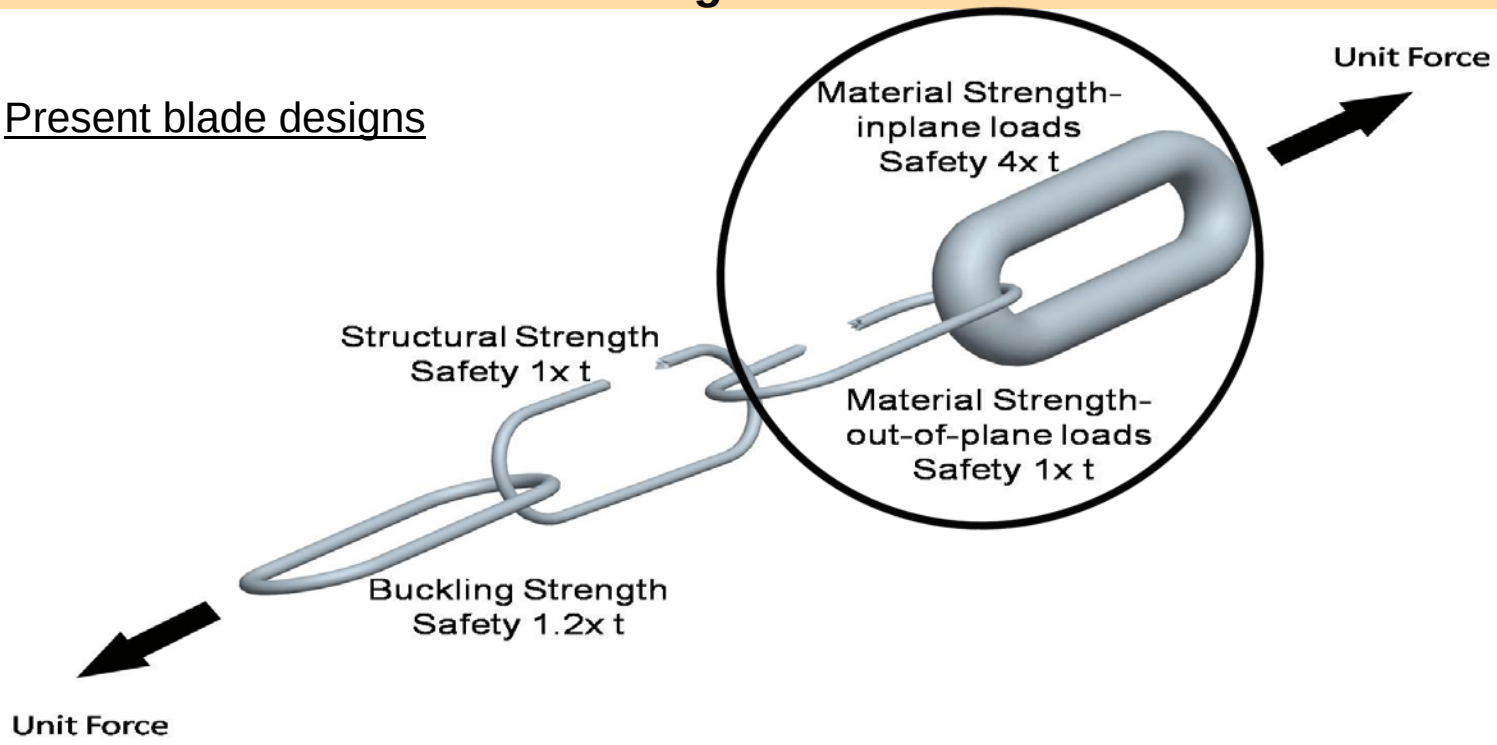




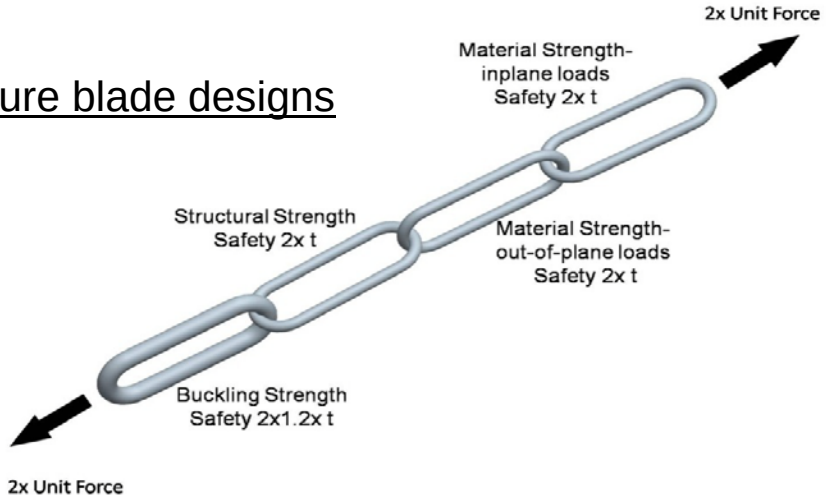
Reference. Clements LL, Moore RL. Composite Properties for E-Glass Fibers in A Room-Temperature Curable Epoxy Matrix. Composites 1978;9(2):93-9

Material strength divided into two chains

Present blade designs



Future blade designs

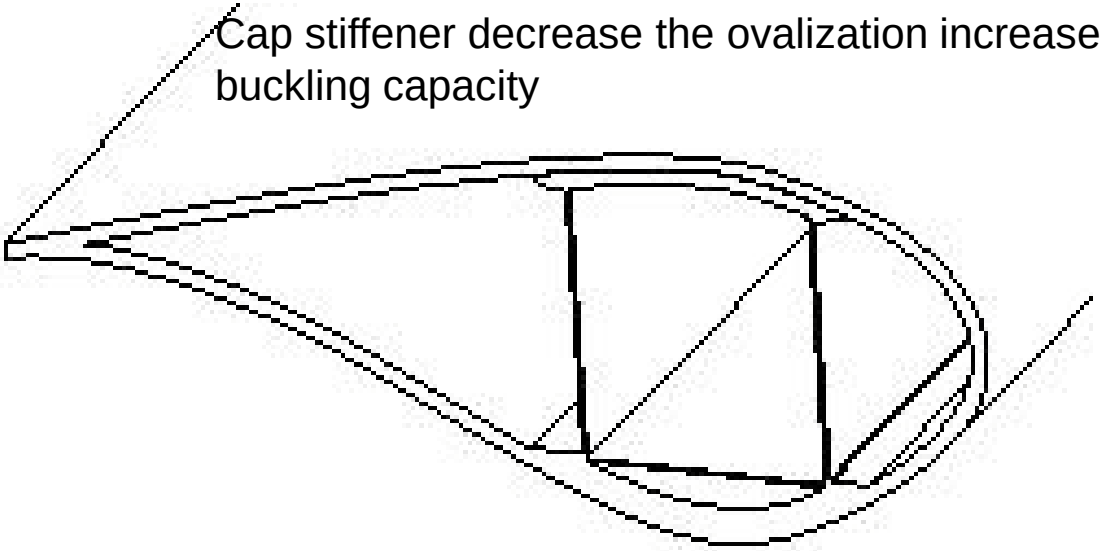


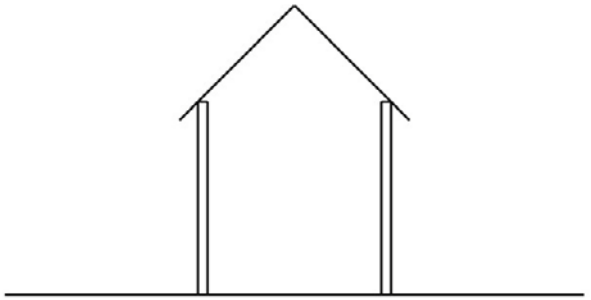
Material strength can be divided into two groups:

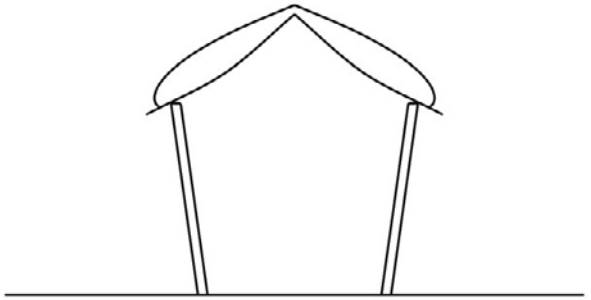
- Inplane strength (in the fiber direction)
- Interlaminar failure or tension failure transverse to the fibre direction

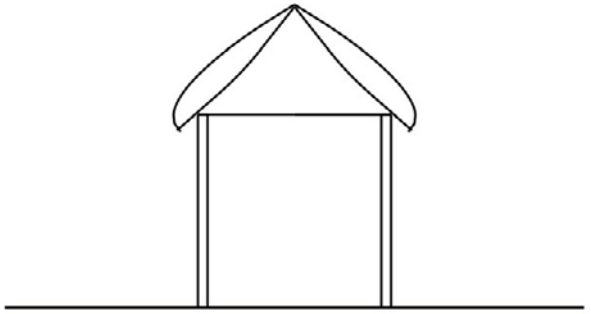
Interlaminar failure in caps can be solved by cap reinforcements

Cap stiffener decrease the ovalization increase the buckling capacity

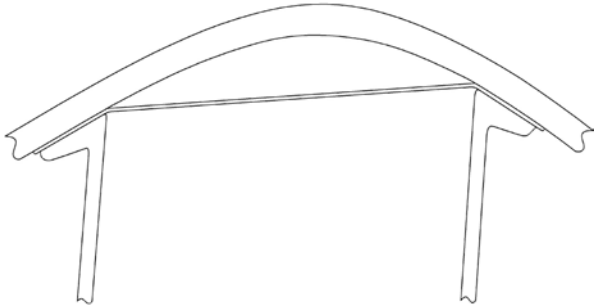




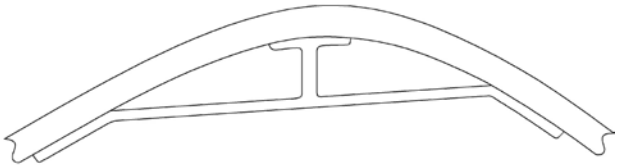




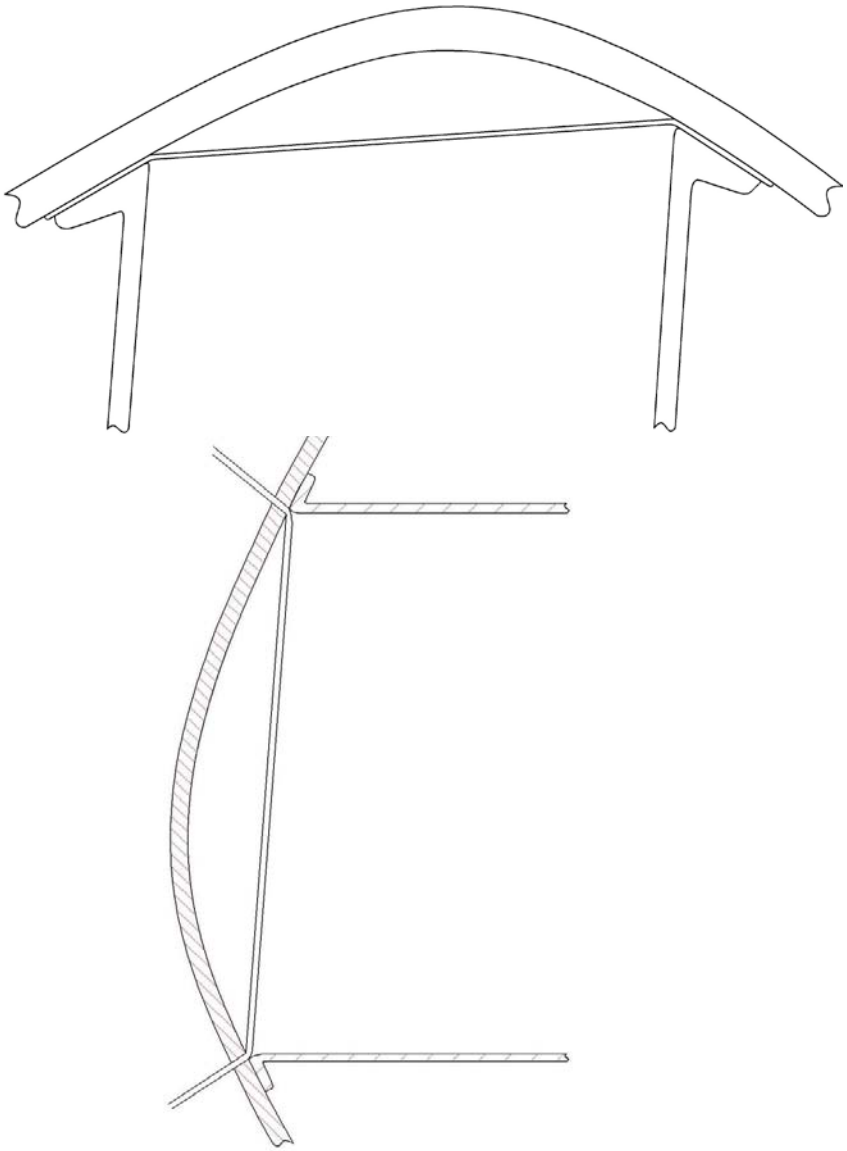
Possible execution:
Dry fibre mat



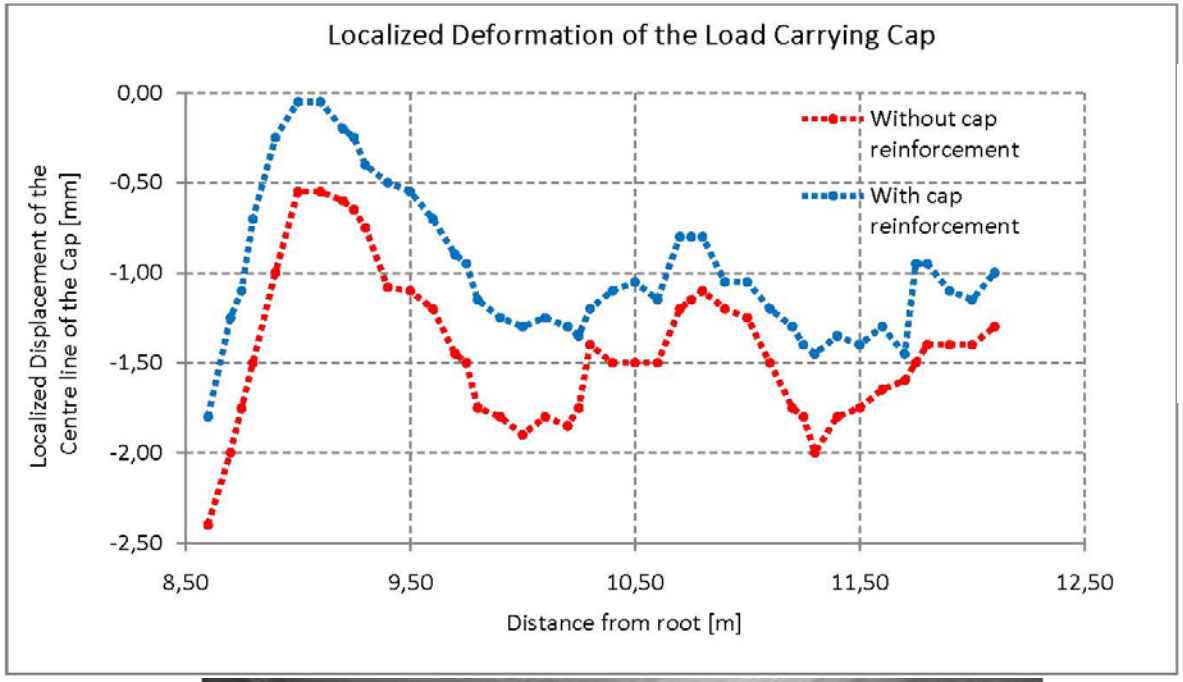
Alternative execution:
Pultruded profile

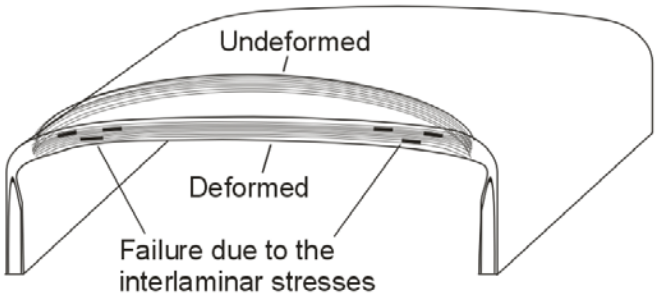


Proof of concept of the cap reinforcement

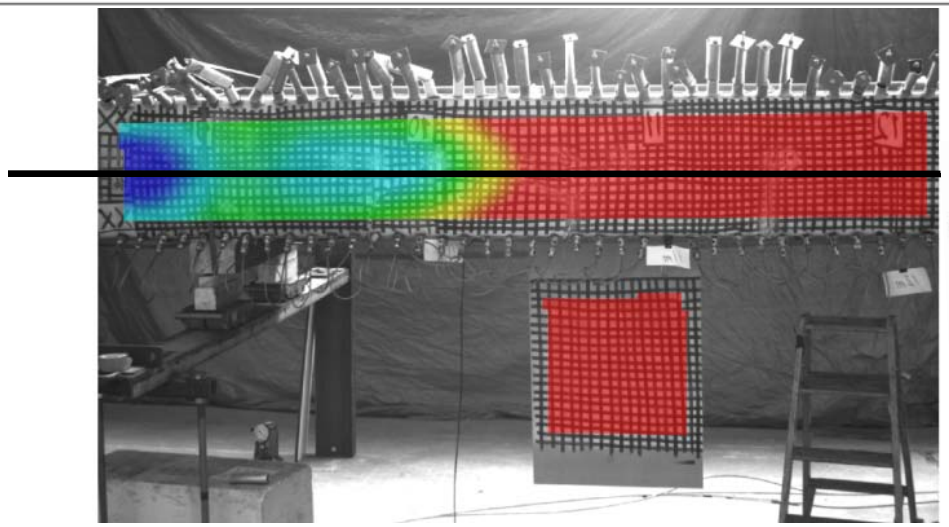


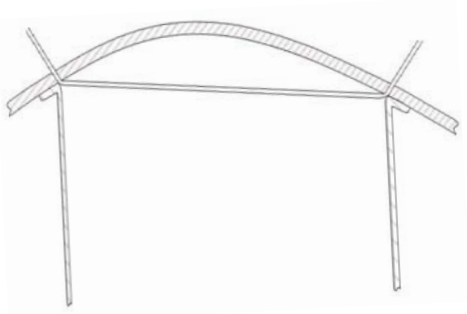
Proof of concept for the cap reinforcent – Cap deformations reduce considerably

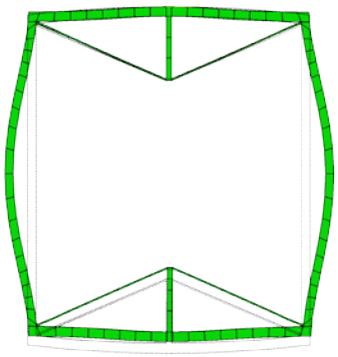




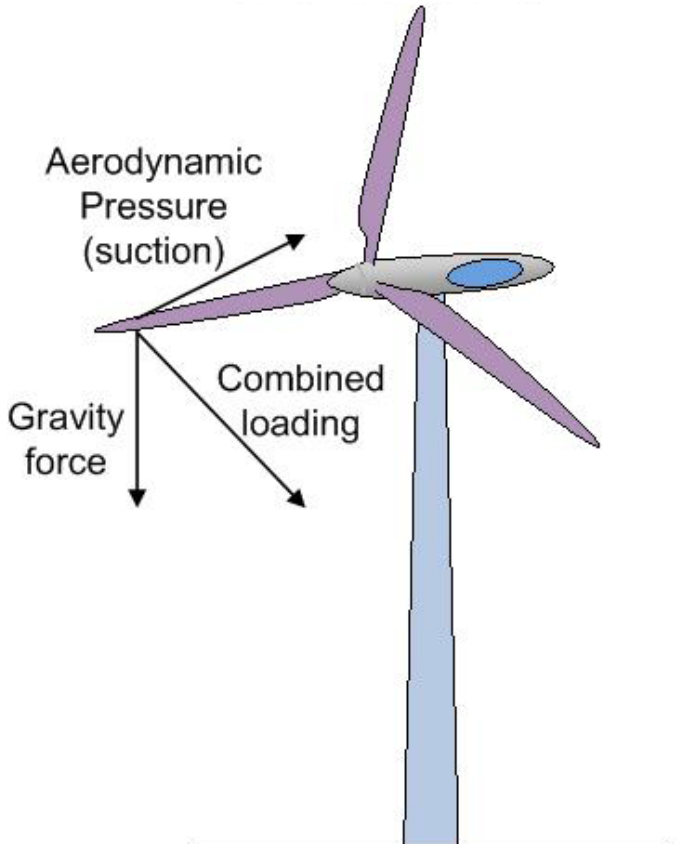
The deformation of the cap is reduced by approx. 30-40%!!

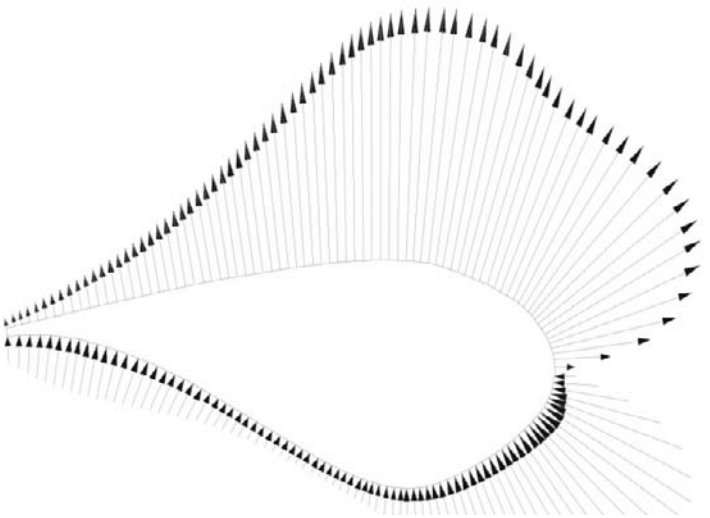


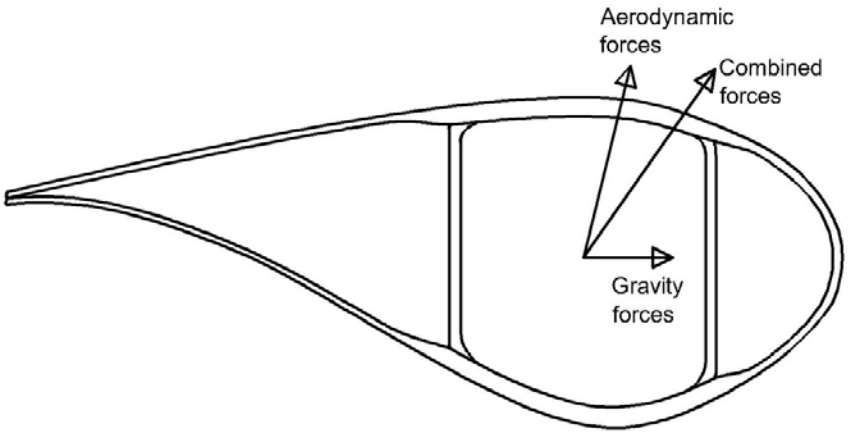




Combined flap- and edgewise loads distort the profile



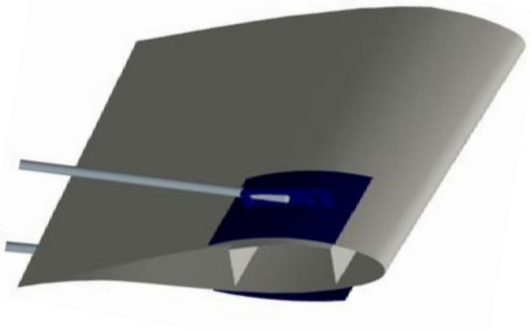


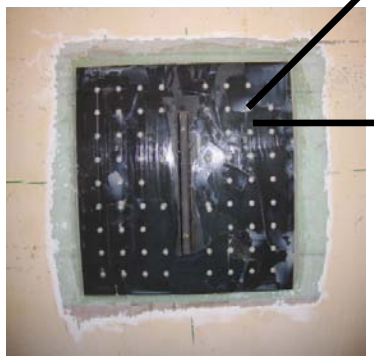


Combined gravity and aerodynamic forces result in a load component different from the traditional flap- and edgewise loads applied in full-scale test

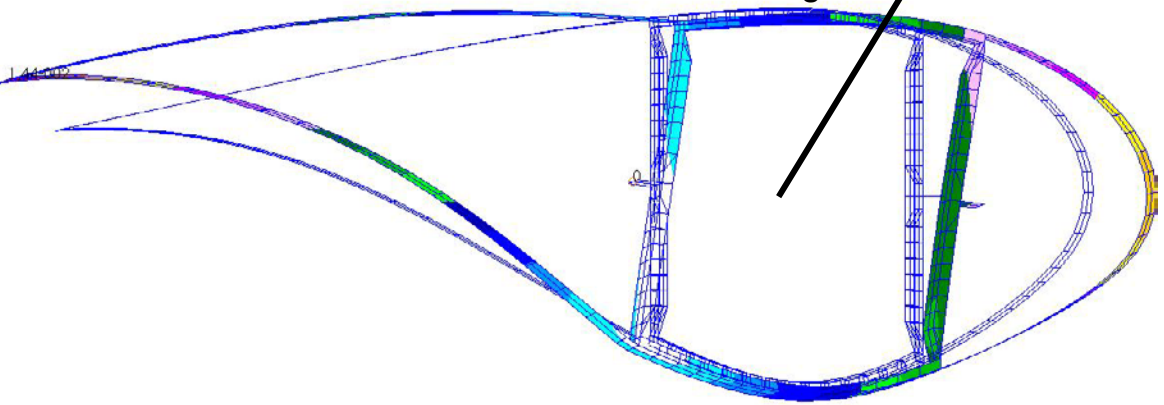
Clamps which are used in full-scale test prevent shear distortion failure

Loading clamps which are used in commercial test





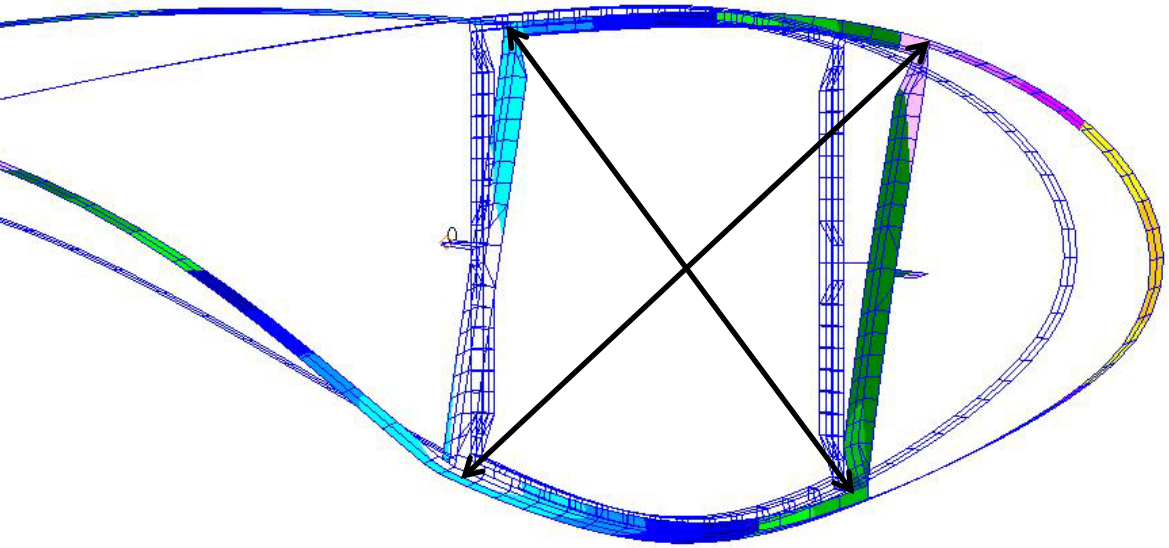
Combined flap- and edgewise loading



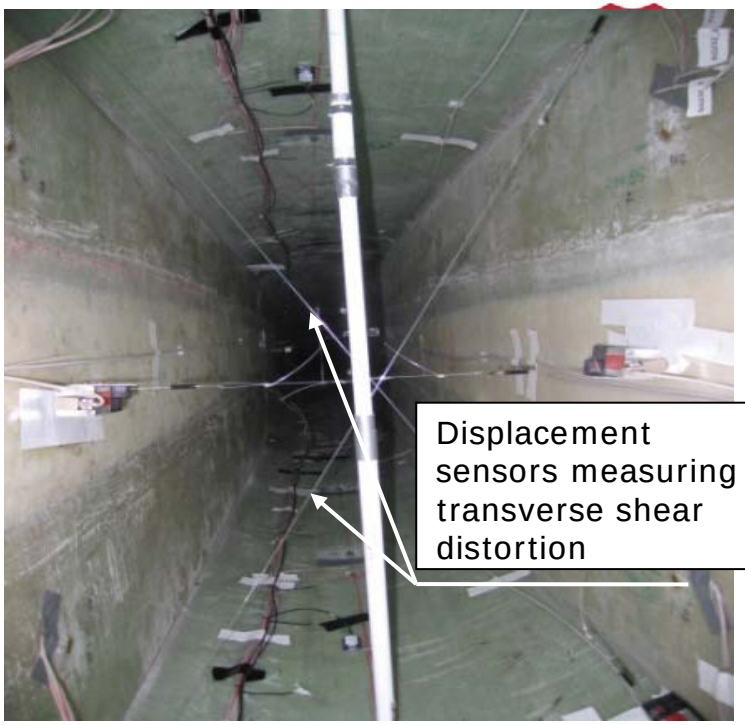
New load clamps are used in the new full-scale test facility at Risø DTU. The anchor plates allow the blade to distort.

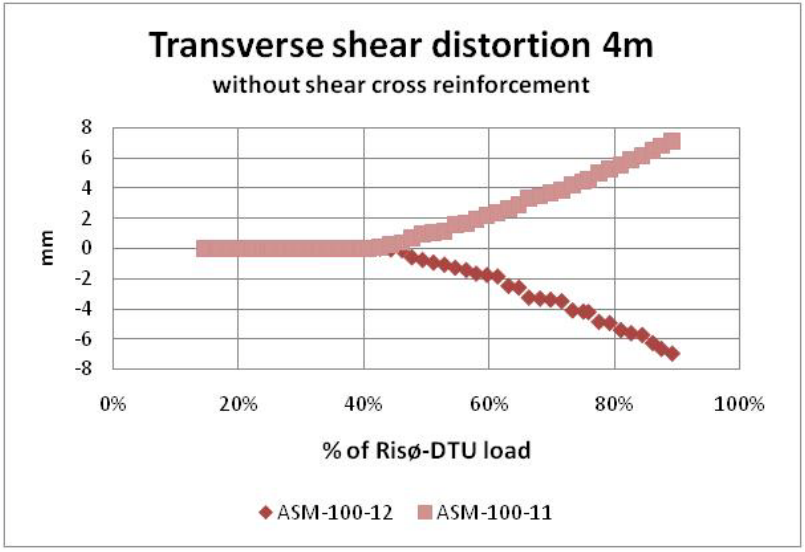
An important for Risø task is to give input to future certification rules

Transverse shear distortion of the cross section



Diagonal displacement sensors measure transverse shear distortion

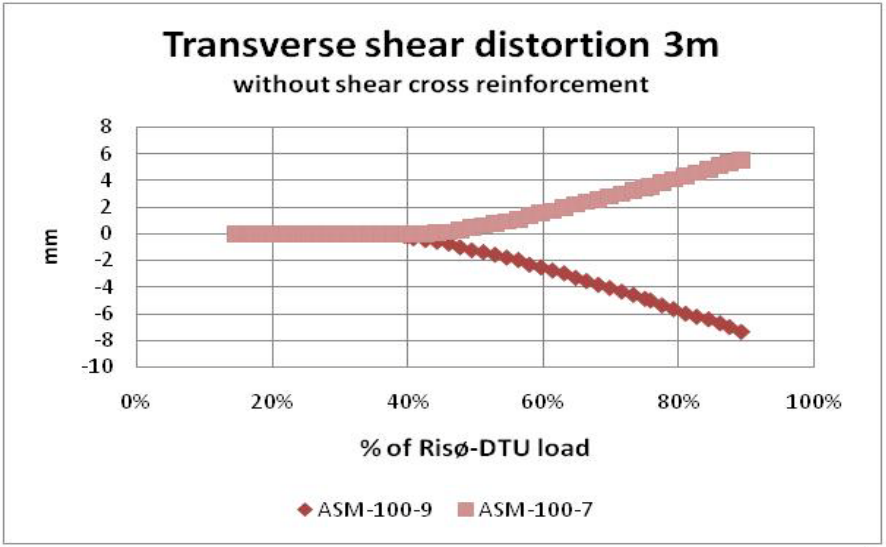


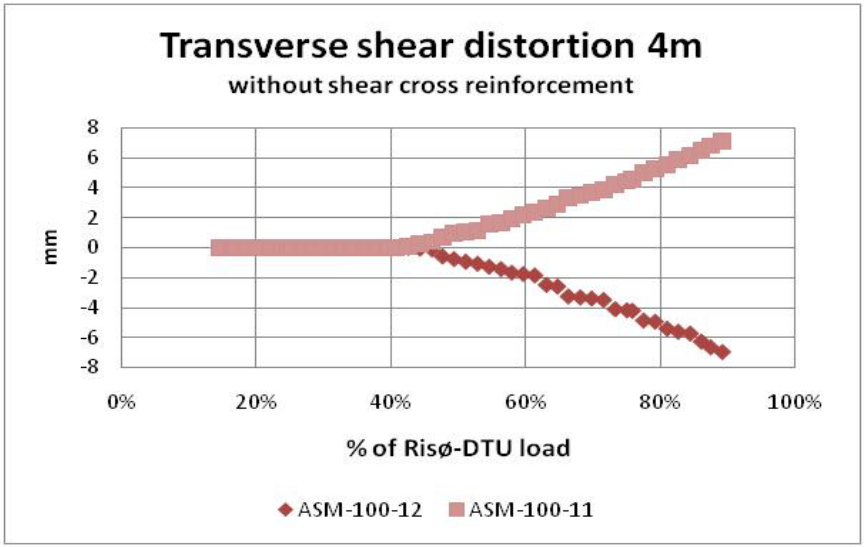


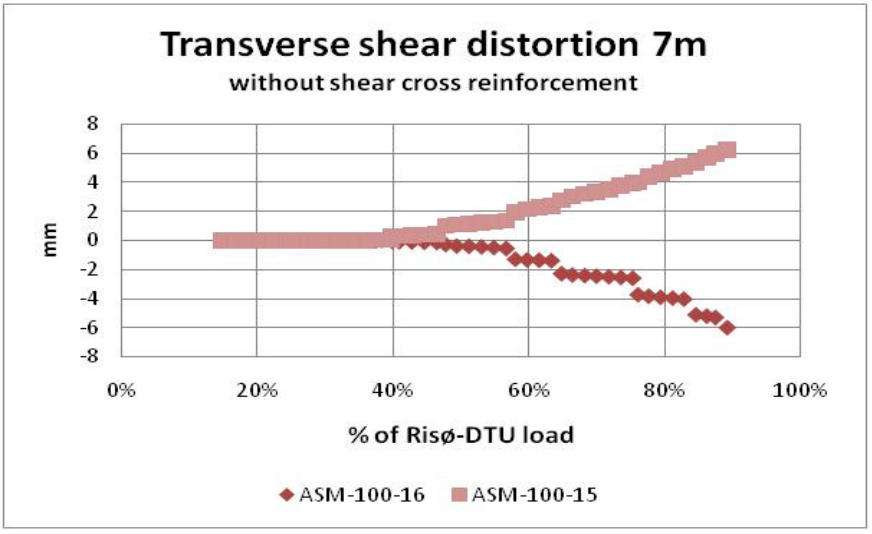
Conclusion:

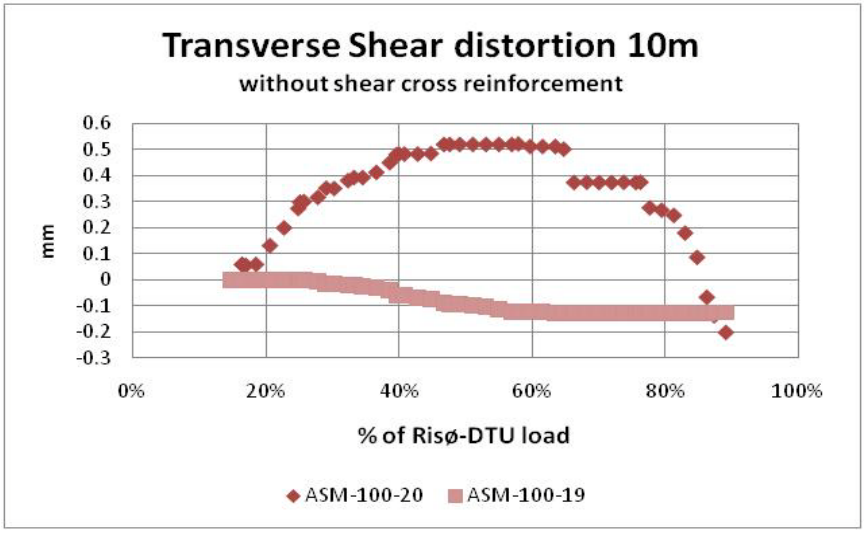
Shear distortion failure do not seem to be critical for a 34m blade but maybe for a larger blade.

Transverse shear distortion of the cross section



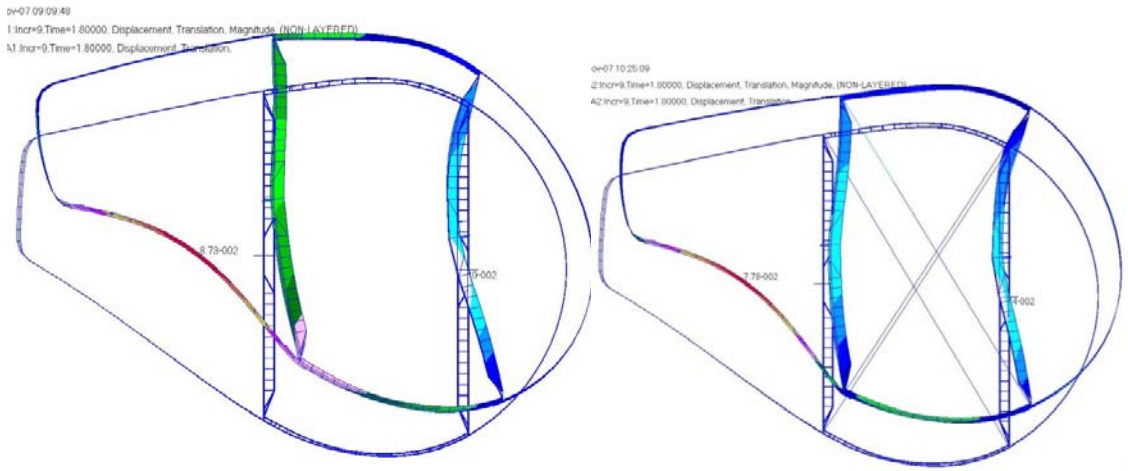




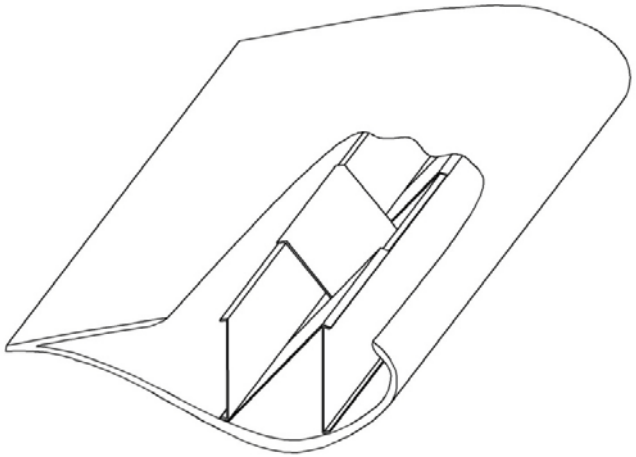


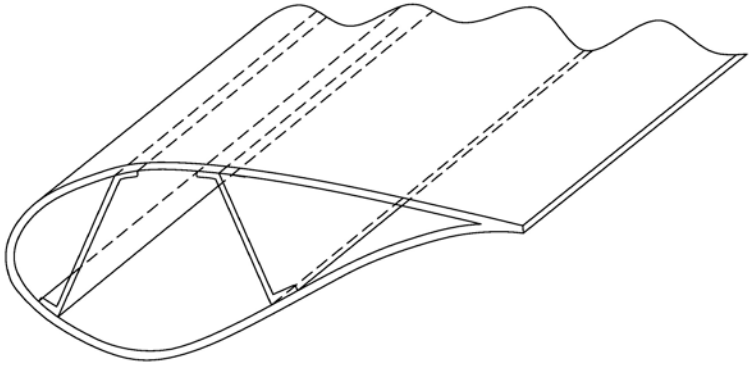
The sections distort differently

Risø DTU patents reduce the risk for transverse shear collapse



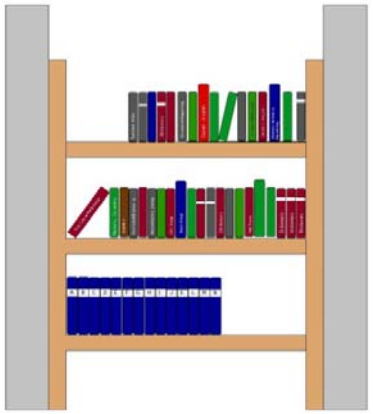
The shear cross invention prevents the profile transverse shear distortion



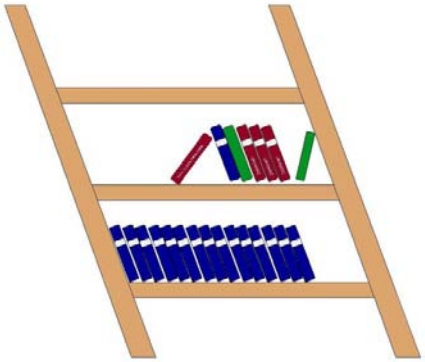


Alternative to cross reinforcement

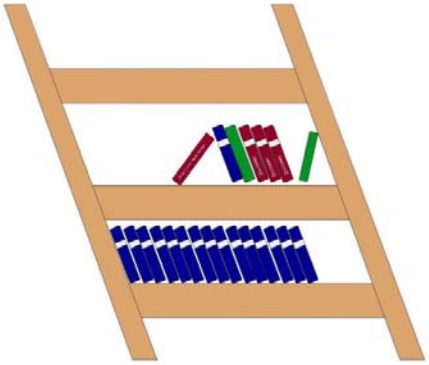
Cartoon illustrate the unused potential in nowerdays blades



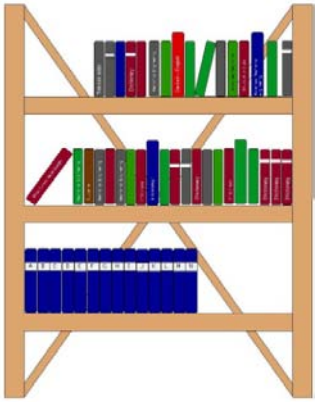
Full-scale test using traditionally clamps



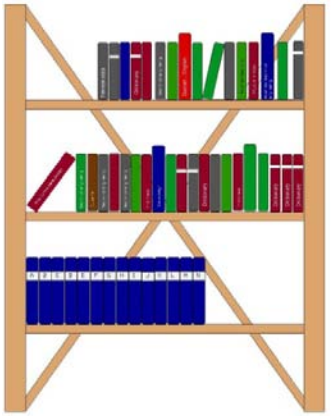
Blade distort in an extreme wind condition



Still distort after the caps has been increased in thickness



Risø DTU Inventions prevent the blade to fail in transverse shear distortion



The thickness of the caps can be reduced together with extra reliability is obtained

Research project – Innovative Wind Turbine Blade

- The research project “Demonstration of new blade design using manufacturing process simulations” started in July 2009 supported by Danish Energy Agency through the Energy Technology Development and Demonstration Programme (EUDP 2009). .

-The blade is designed at Risø DTU by use of the new design philosophy.

- The manufacturing is performed by SSP Technology A/S. The support is gratefully acknowledged.

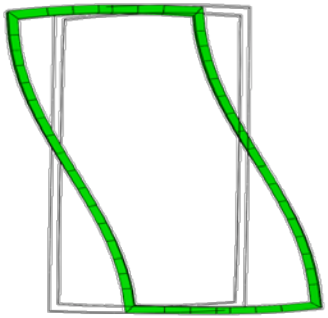
- The blade is a 2.2MW wind turbine certificated to Class 1 where the extreme loads include loads such as a hurricane etc.

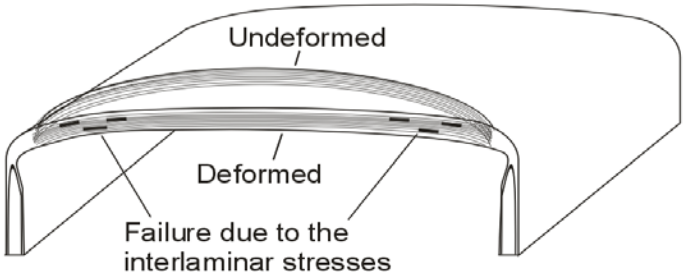
- The blade is in the range of 40-45m (actual length is confidential)

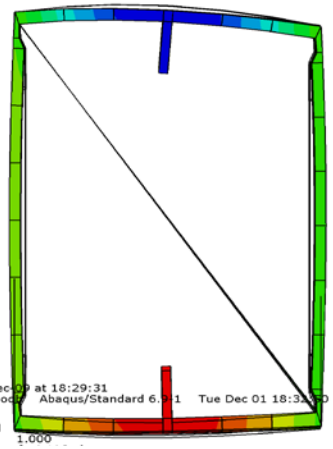
Use of internal structure to prevent non-linear failure behaviour

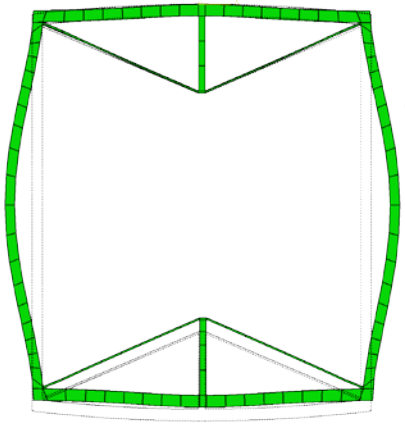
- Based on the new design philosophy which include nonlinear failure mechanisms a 40m load carrying box girder has been designed by Risø DTU

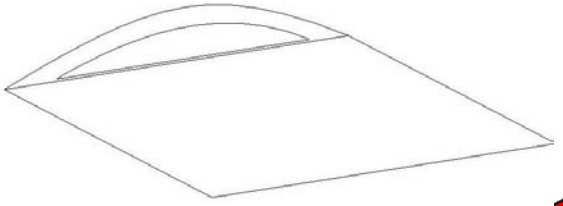
- The box girder include 3 innovative solutions patented by Risø DTU



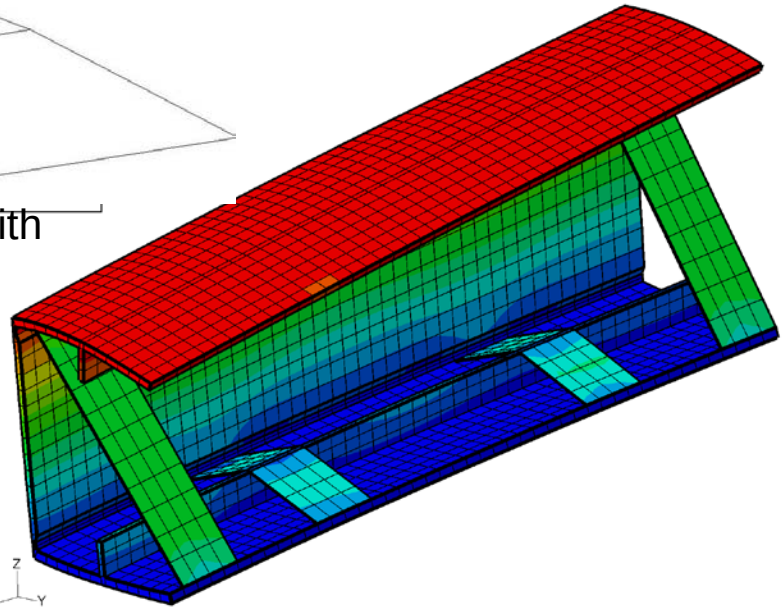








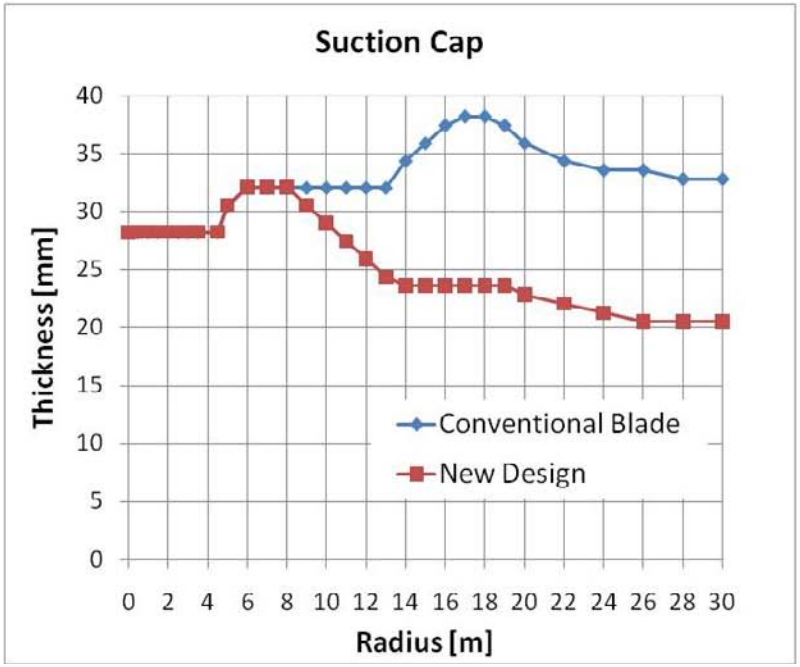
Cap stiffener with
curved aerofoil

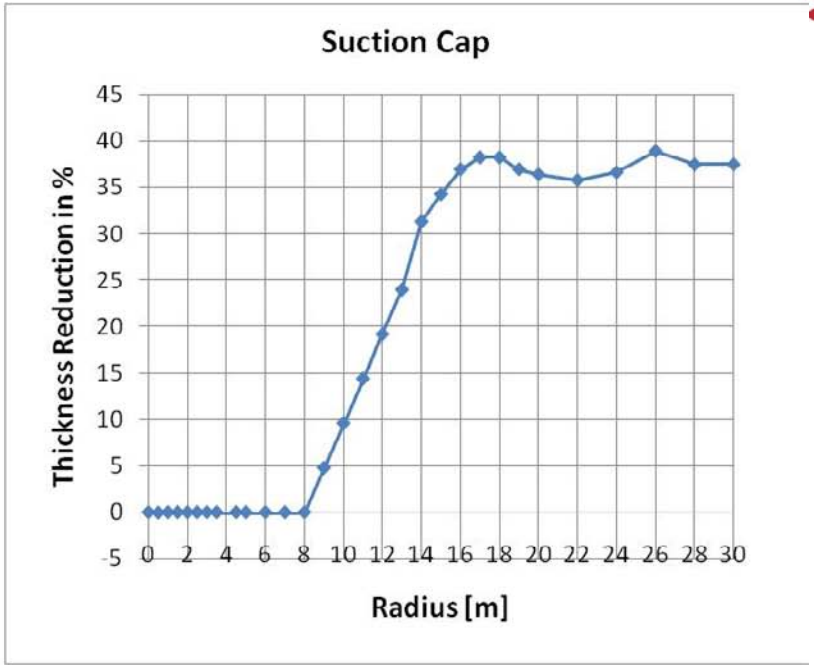


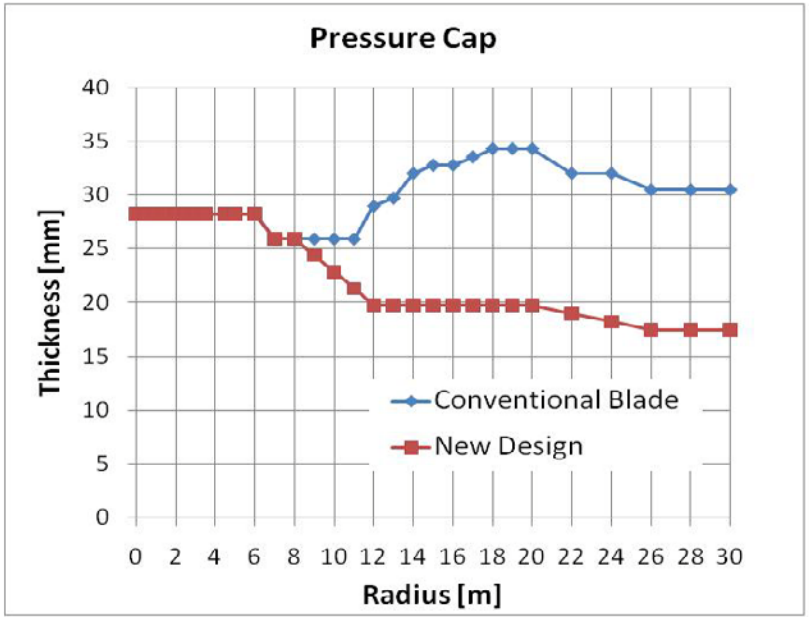
Diagonal prevent
transverse shear
distortion

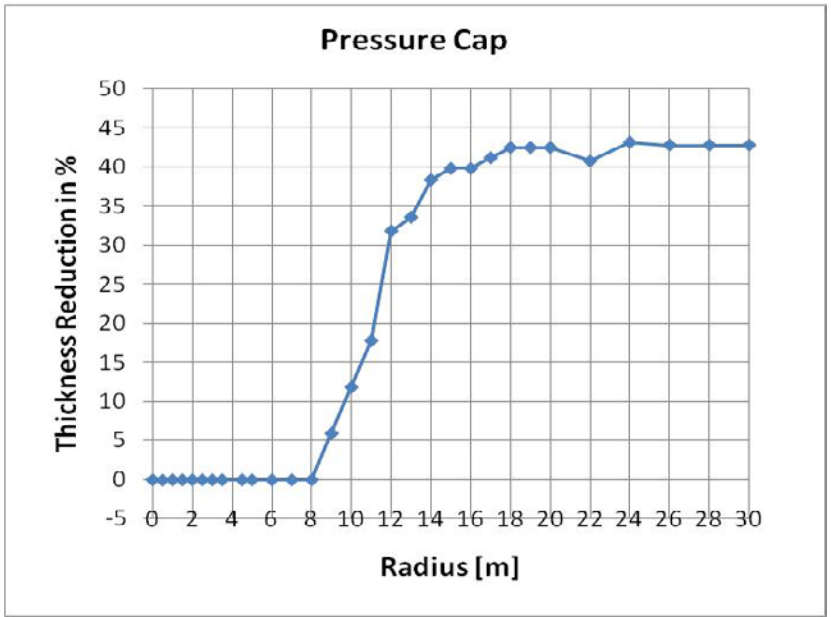
Cap stiffener with
flat aerofoil

Main results – weight saveness



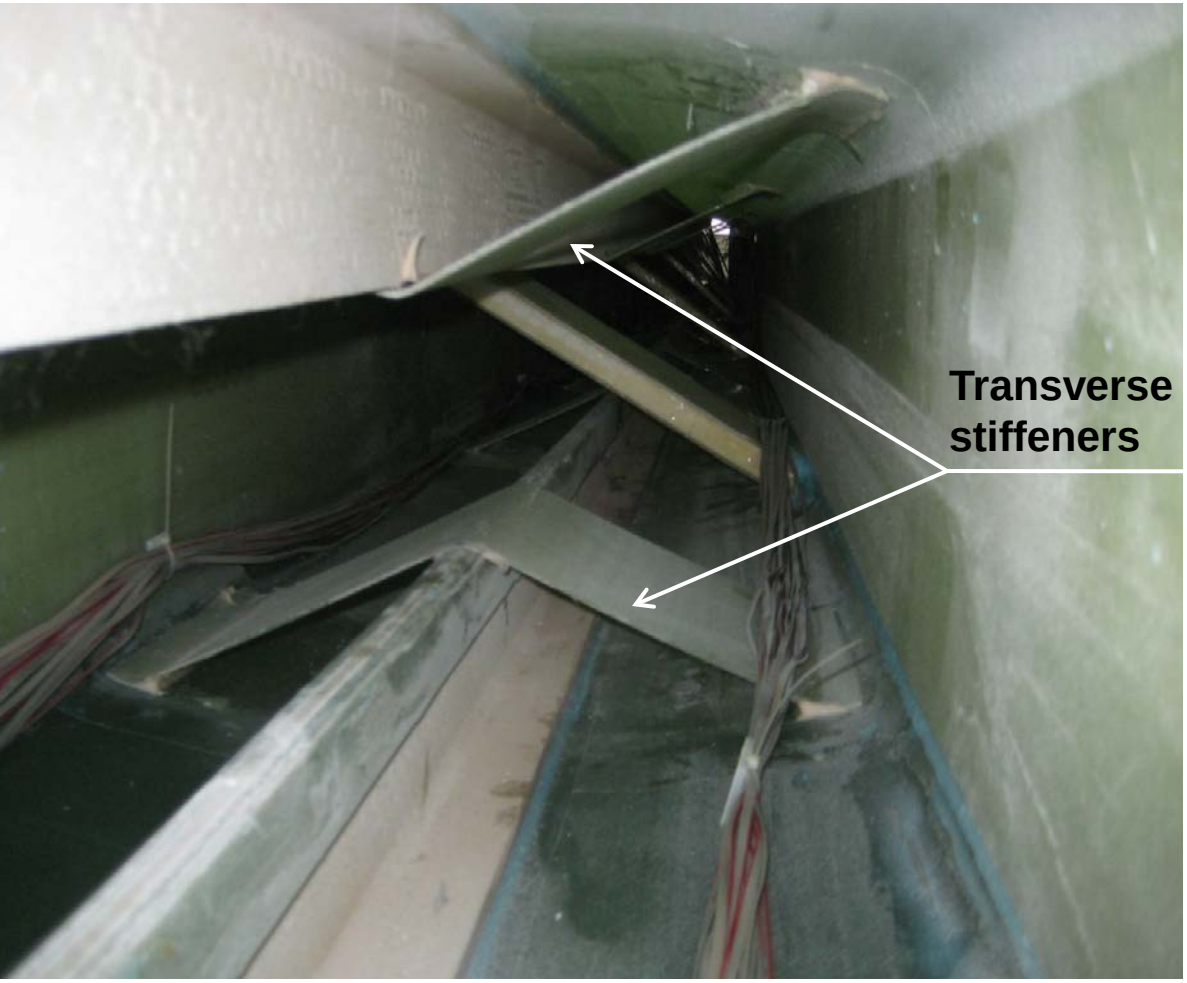






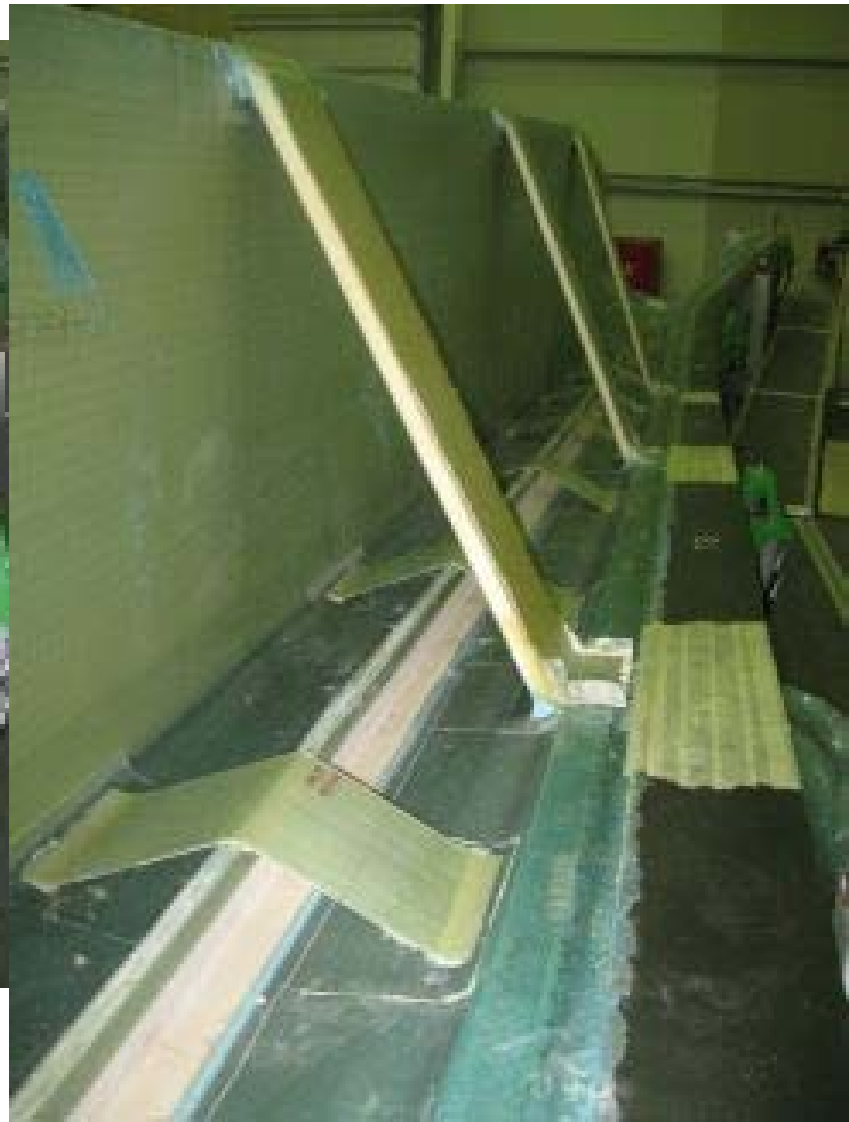
Manufacturing

SSP-Technology has recently finished the manufacturing.

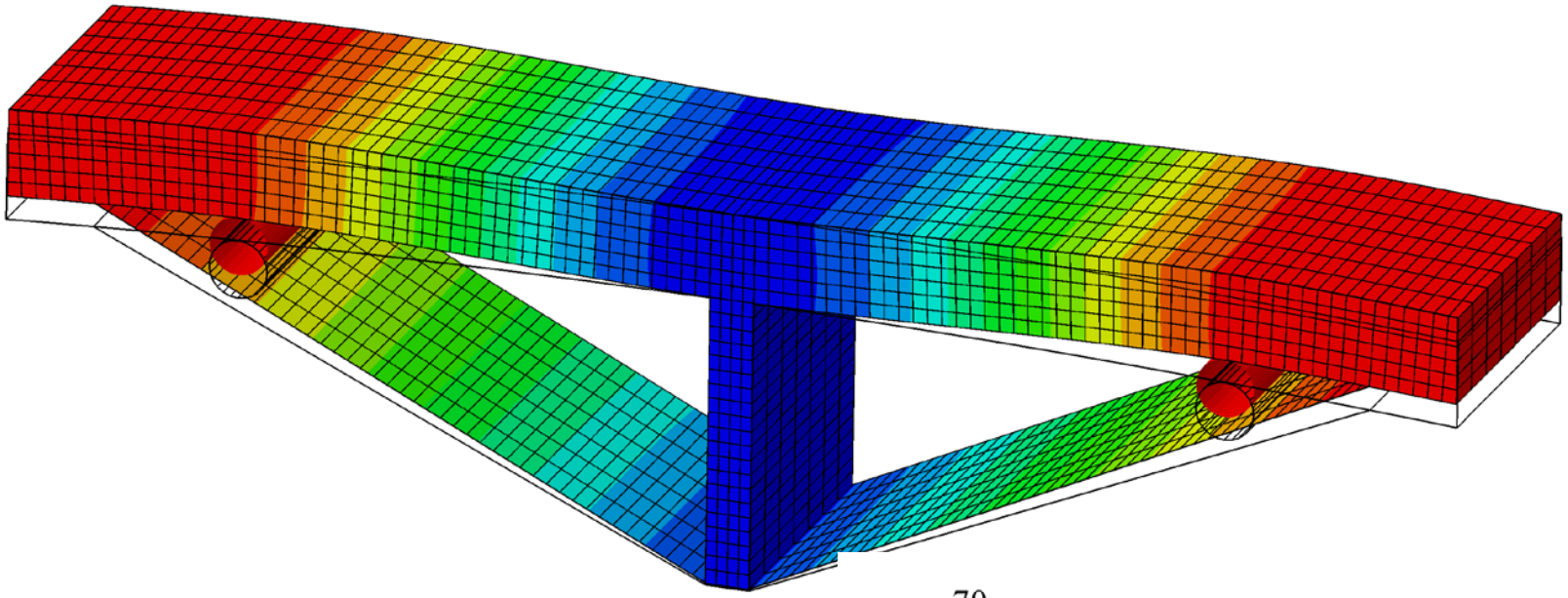


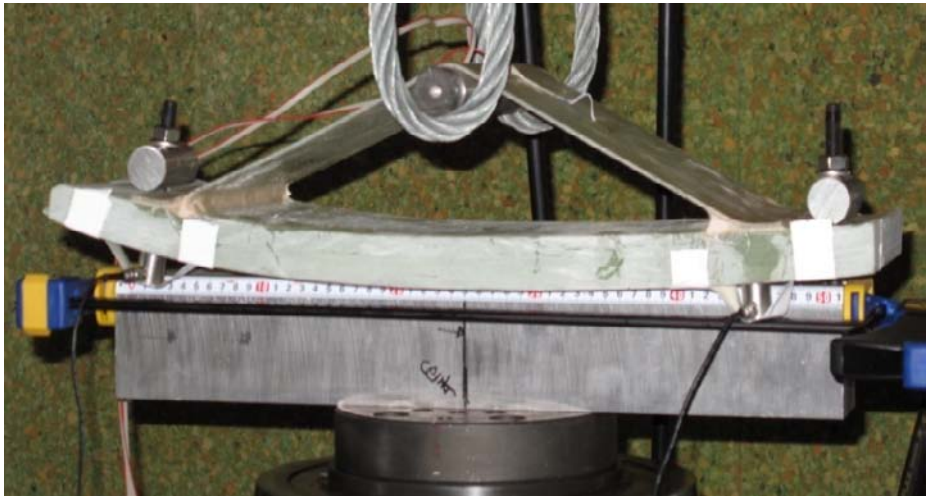
Manufacturing

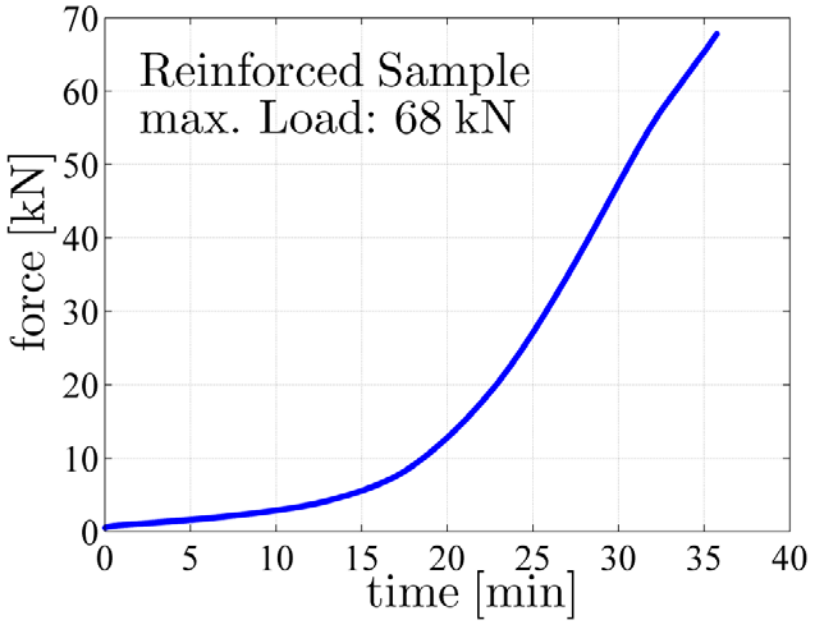
The box girder will be tested in Risø's full-scale test facility in Autumn 2010



Sub component test to verify strength of the adhesive joints



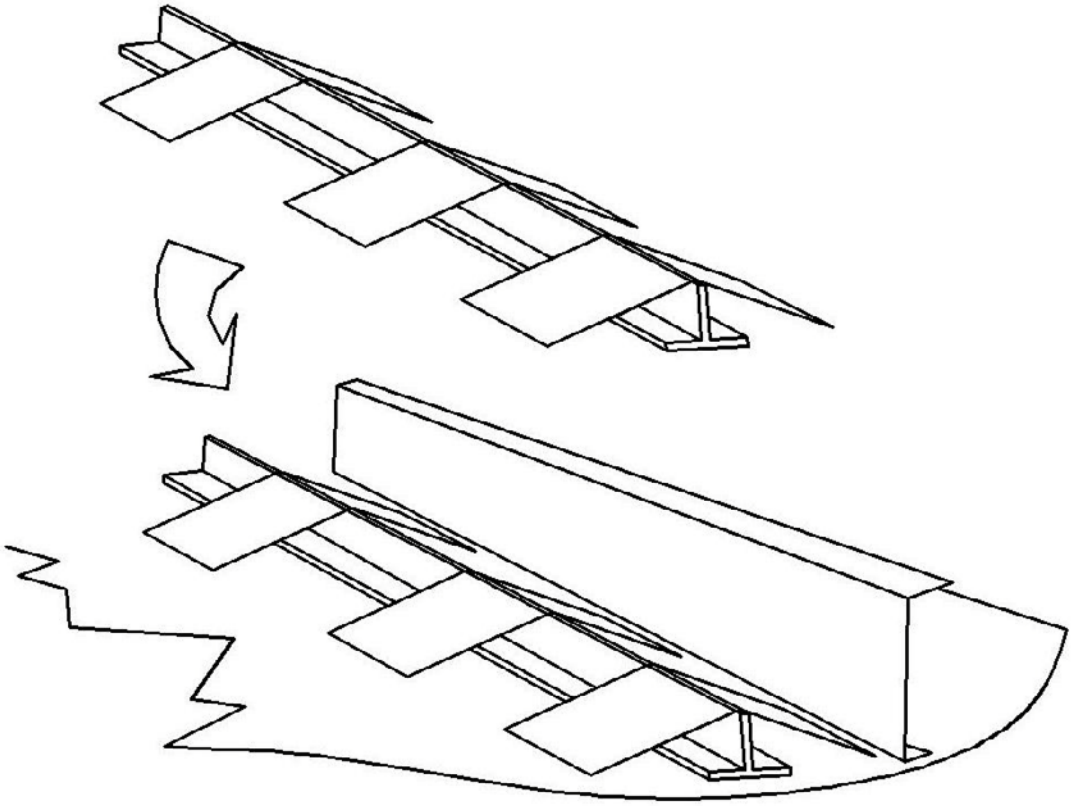




Future work

- The strength of box girder will be validated in Risø DTU's research facility in Summer 2011 .

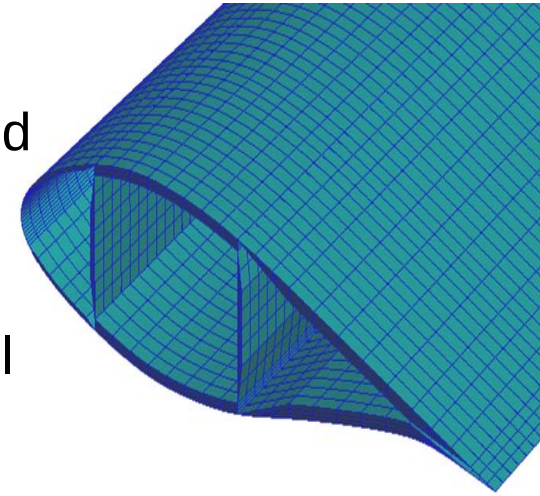
- The manufactured parts must be optimized so it is fast to insert internal structure in the blade when the blade is in the mold



Summary - Why do we first observe these failure types now?

Non-linear geometric simulations are needed to get a full picture of representative failure modes

Combined load cases with realistic boundary supports result in other failure modes than required by design and testing procedures today



New design and testing rules must be included if the full potential of the material should be used

Full-scale tests with more (and advanced) measuring equipment supported by FE-results give the optimal value.

Risø DTU believes that the repair costs can be reduced and that the weight of nowadays wind turbine blades can be reduced significantly!

Thank you for your attention

Any Questions?

Any questions please email or call
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Wind Turbine Structural Path Stress & Fatigue Reductions Resulting from Active Aerodynamics

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WINDPOWER 2011
May 23-25, 2011
Anaheim, CA

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

NNSA National Nuclear Security Administration
Sandia National Laboratories

Acknowledgements

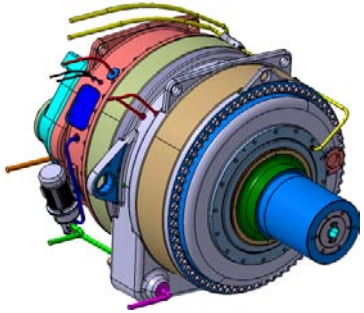
- **Brian Resor**
  - *Sandia National Laboratories, Albuquerque, NM.*

- **Zachary Wright, Ashley Crowther and Chris Halse**
  - *Romax Technology Ltd., Boulder, CO*

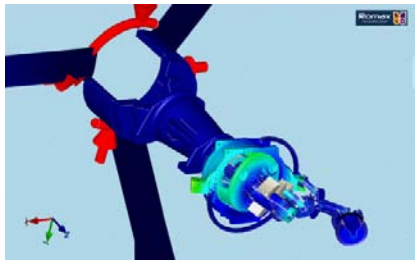
- **SMART Team Members**
  - *David Wilson, Jonathon Berg, Matt Barone, Joshua Paquette, Wesley Johnson, Mark Rumsey, Jonathon White*

Romax Technology

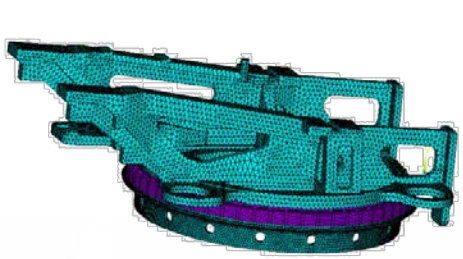
- Rotating machinery experts with 200 employees worldwide
- Boulder office dedicated to serving US customers for wind engineering



Gearbox Design



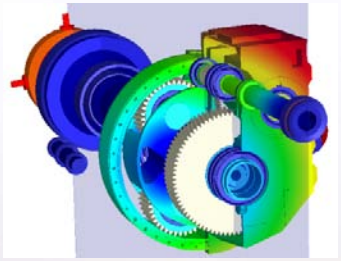
Drivetrain dynamics

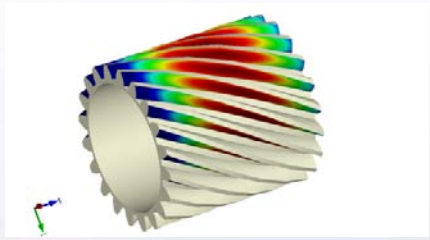


Pitch and Yaw System Design and Analysis

Instrumentation

Drivetrain inspections





Gear and bearing durability and vibration

- Contact: Ashley Crowther, VP Engineering – Wind
  ashley.crowther@romaxtech.com, +1 303 562 6064

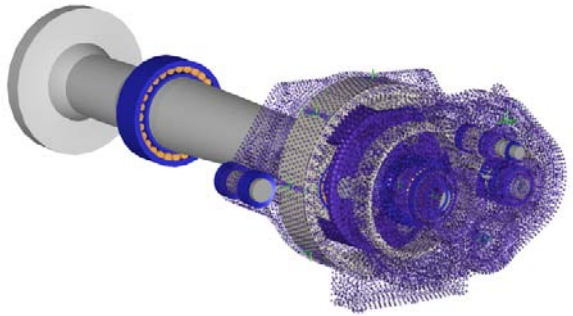
Sandia National Laboratories

Presentation Outline

- **Review of GRC & Active Aerodynamic blade Load Control**
- **Drive train model**
- **Turbine model**
- **Analysis**
- **Impact of AALC**
  - **hub**
  - **gearbox**
  - **extreme bedplate loads**
- **Summary**
- **Conclusions & future work**

Motivation for Work

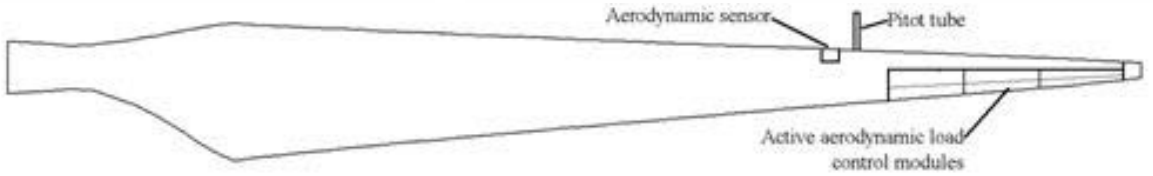
- **Industry has been plagued with numerous gearbox failures**
- **NREL established the Gearbox Reliability Collaborative to address this issue**
  - **heavily instrumented gearbox**
  - **extremely detailed gearbox model (Romax)**
  - **model validated against experimental data**



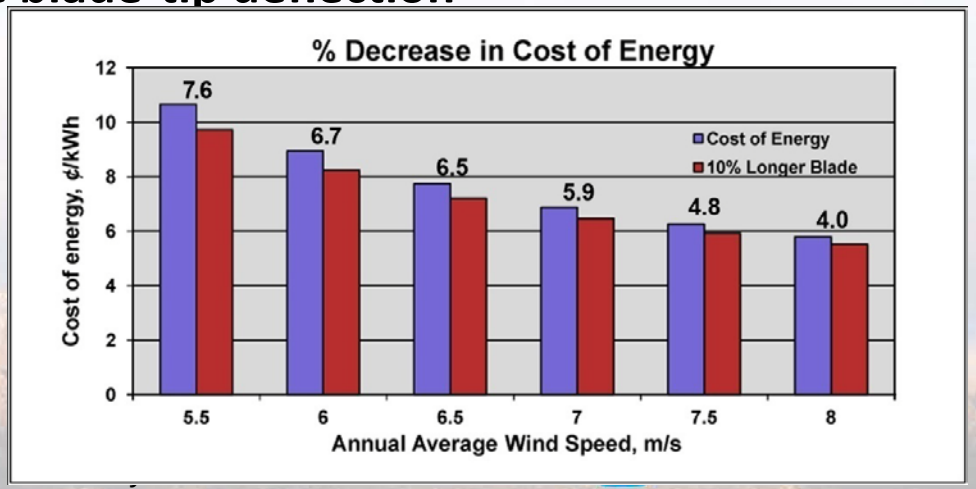
- **Simulations reveal bearing loads quite sensitive to non-torque loading**
  - **main shaft bending**
  - **out of rotor plane moments**
  - **non-uniform wind loading**

Impact of Active Load Control on COE

- **"20% by 2030" report: Decrease in blade fatigue loading will yield COE decrease**
- **Active Aerodynamic Load Control (AALC)**
  - **sense local loads along blade**
  - **attenuate local loads with fast-acting distributed aero control surfaces**



- **Simulation results**
  - **controller designed to minimize blade-tip deflection**
  - **reduce blade fatigue loads**
  - **reduce turbine COE**

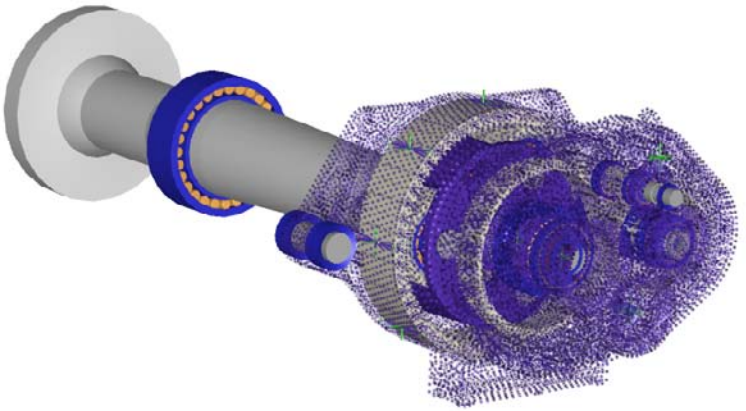


Preliminary work in 2010

- AALC also reduces non-torque loading on drive train (Resor)
- Romax performed limited analysis of impact on gearbox
  - small change in gear stresses due to off-axis loading
  - larger changes in carrier bearing off-axis moments
  - reduction in magnitude of stress cycles on bearings
  - conclusion:
    - may decrease fatigue damage
    - may increase fatigue life
- Conclusions:
  - AALC may mitigate gearbox damage
  - more complete analysis is needed

Gearbox Model

- Finite element representation of shafts
- Solid finite element representation
  - gearbox housing
  - gear blanks
  - planet carrier and torque arms
  - 6DOF spring connections for (elastomeric) trunnion mounts
- Semi-analytical formulations for gears and bearings
  - misalignment
  - area of contact under load
  - gear and bearing microgeometry
  - radial and axial clearances
  - preload and material properties

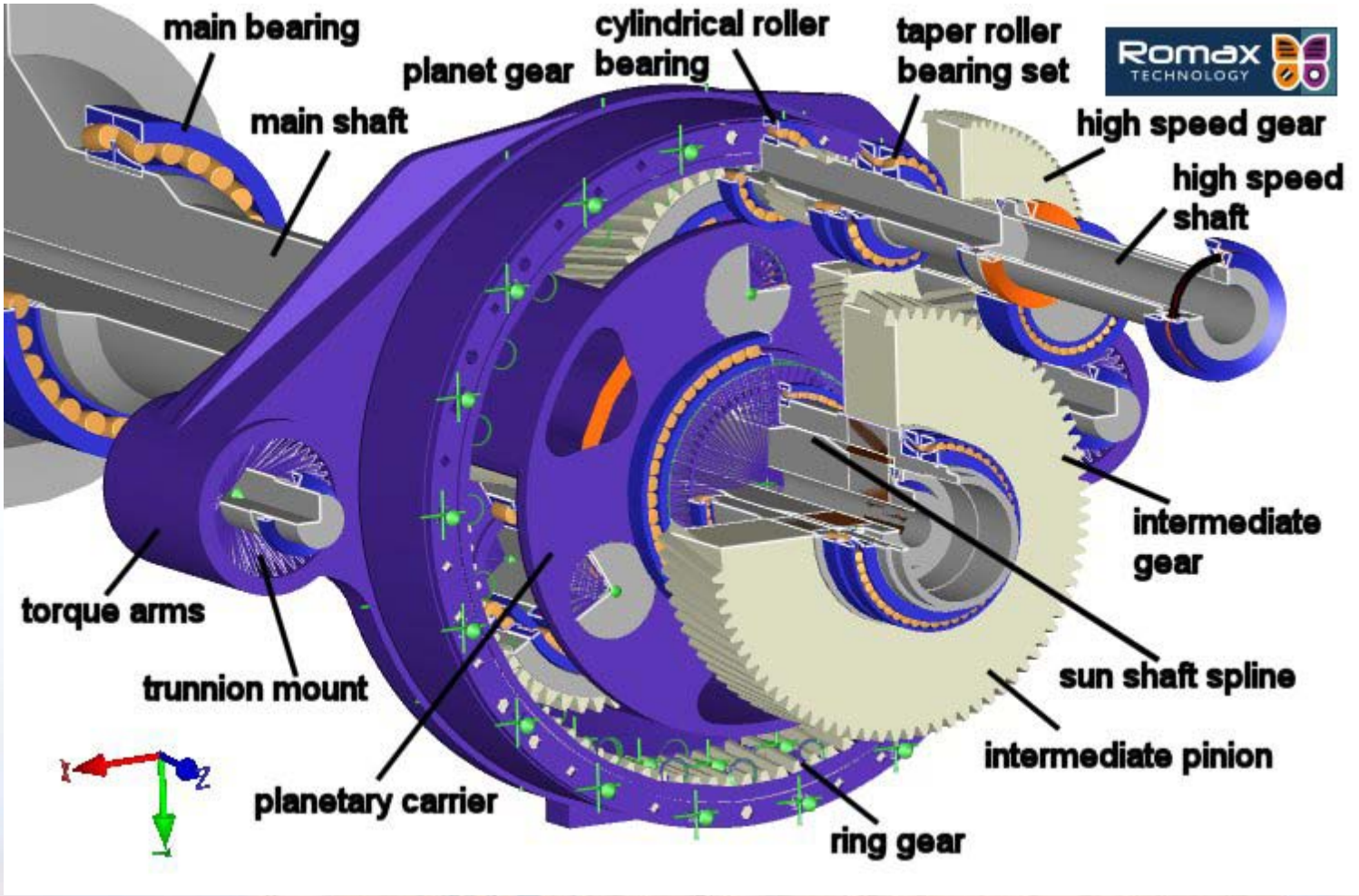


Gearbox model

Current Drive Train Analysis

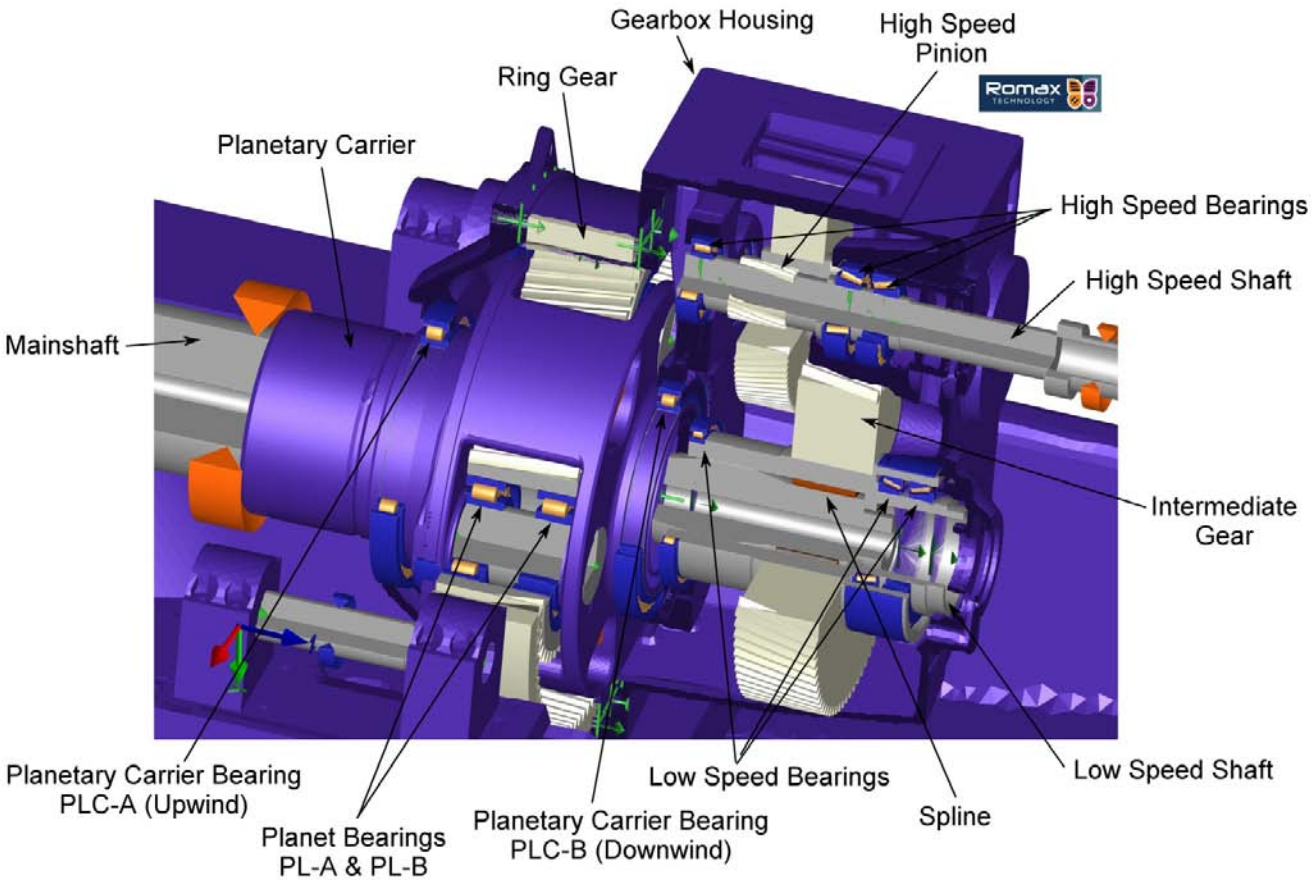
- GRC 750 Turbine
- Gearbox model validated against experimental loads data
- Extended to simulate drive train
  - bedplate
  - hub
  - blade pitch system
- Active pitch control system
- Detailed finite element modelling of all components
- AALC simulations on GRC 750 turbine model
  - reduce blade root flap fatigue loads
- Apply extreme and operating time-series loads to drive train
- Perform strength & fatigue analyses of components

GRC Gearbox Details

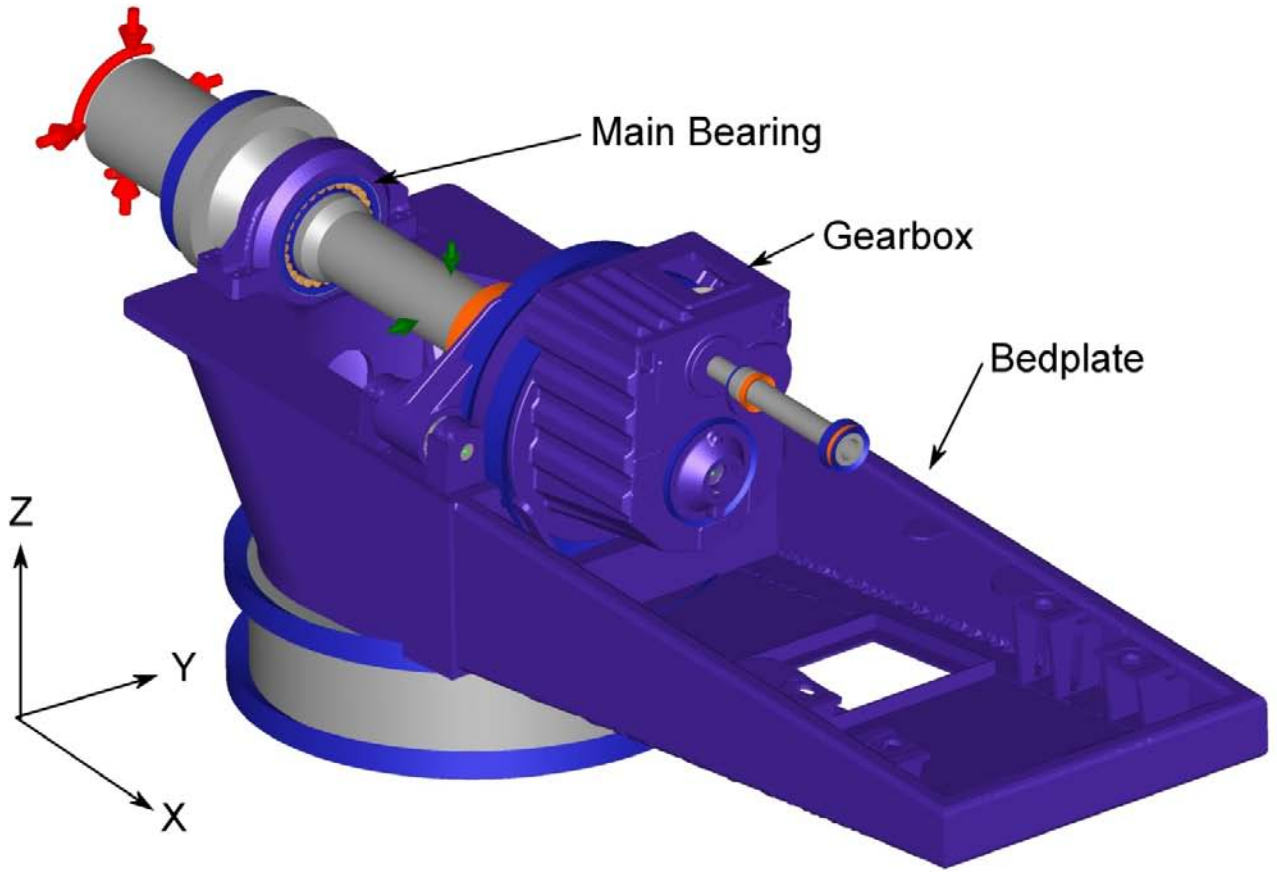


Model of GRC Gearbox

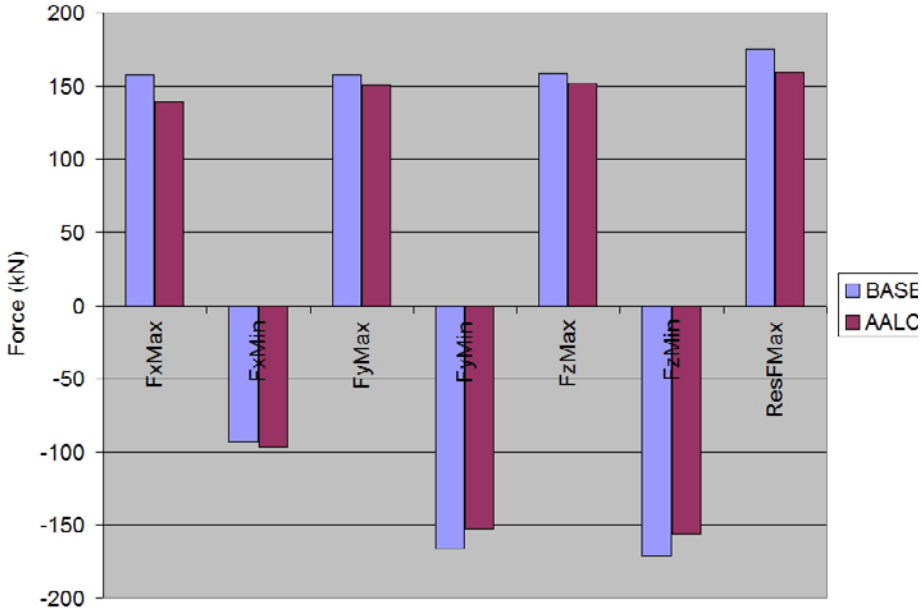
GRC Gearbox Details



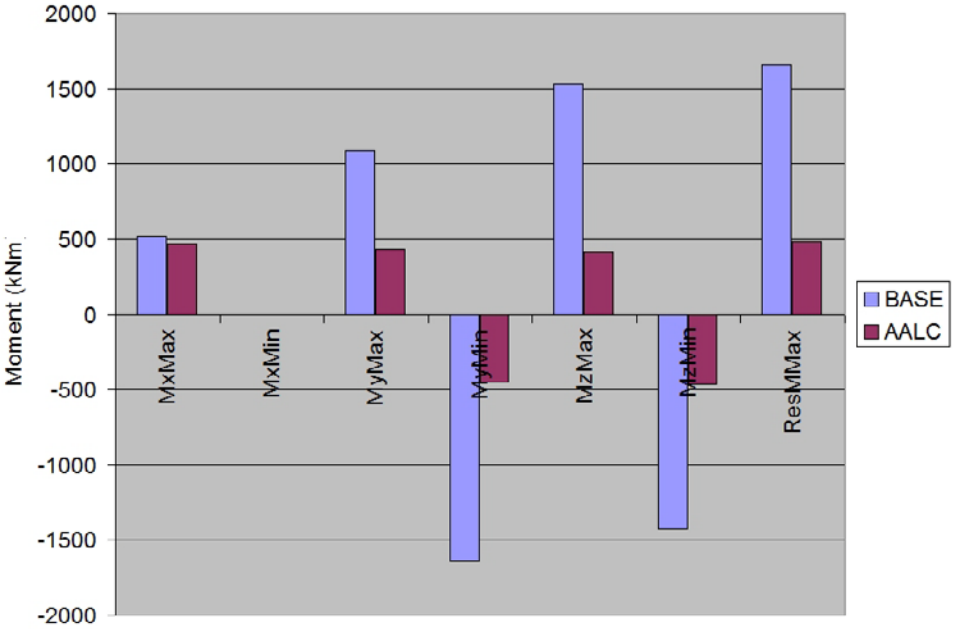
GRC Drivetrain Axis Definition



AALC Impact on Hub Loading

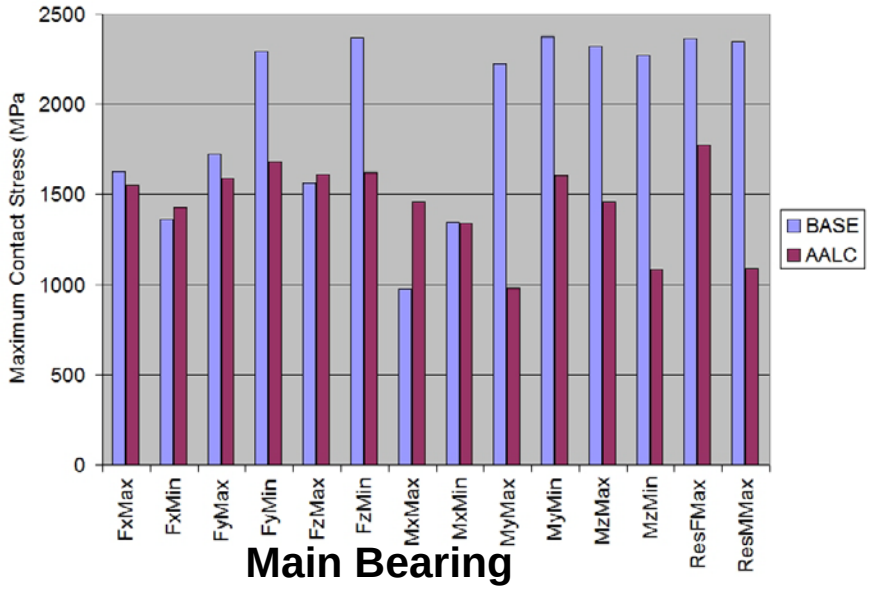


Hub Forces

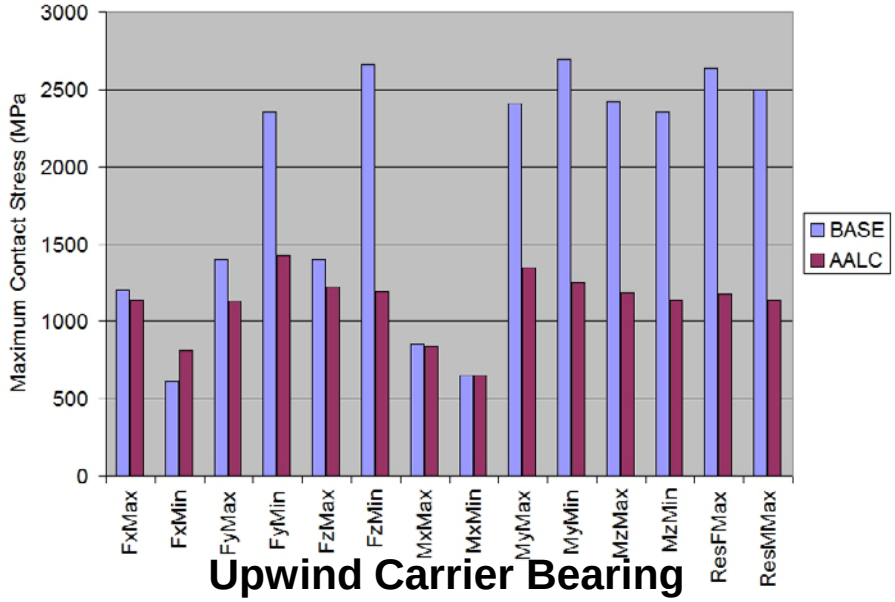


Hub Moments

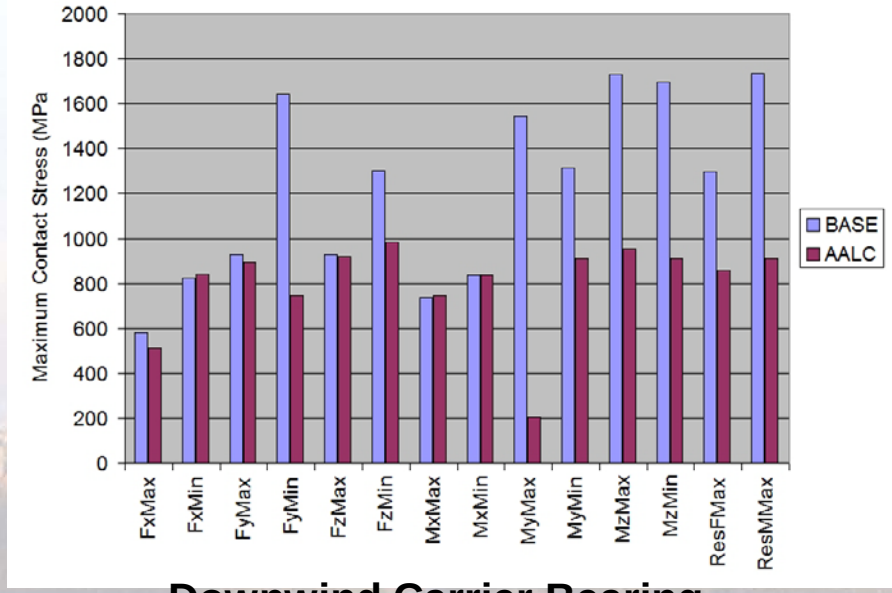
AALC Impact on Bearing Moments



Main Bearing



Upwind Carrier Bearing



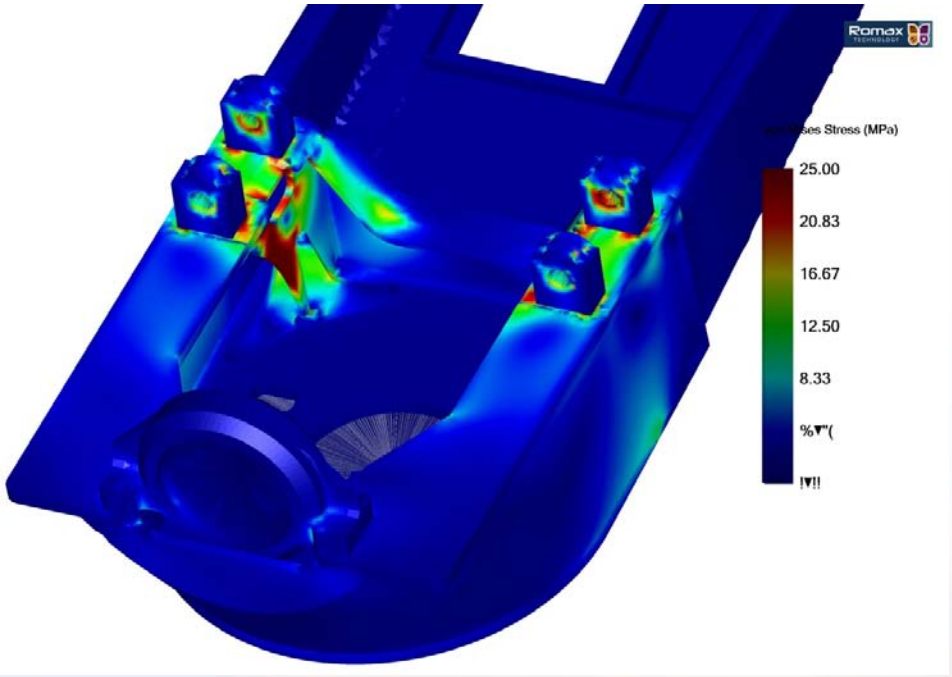
Downwind Carrier Bearing

Sandia National Laboratories

AALC Impact on Bearing Fatigue Damage

Bearing	Relative Change in Fatigue Damage due to AALC (ISO 281)
Main	-7%
Upwind Carrier	-32%
Downwind Carrier	-16%

AALC Impact on Extreme Bedplate Loads - M_{xMax}



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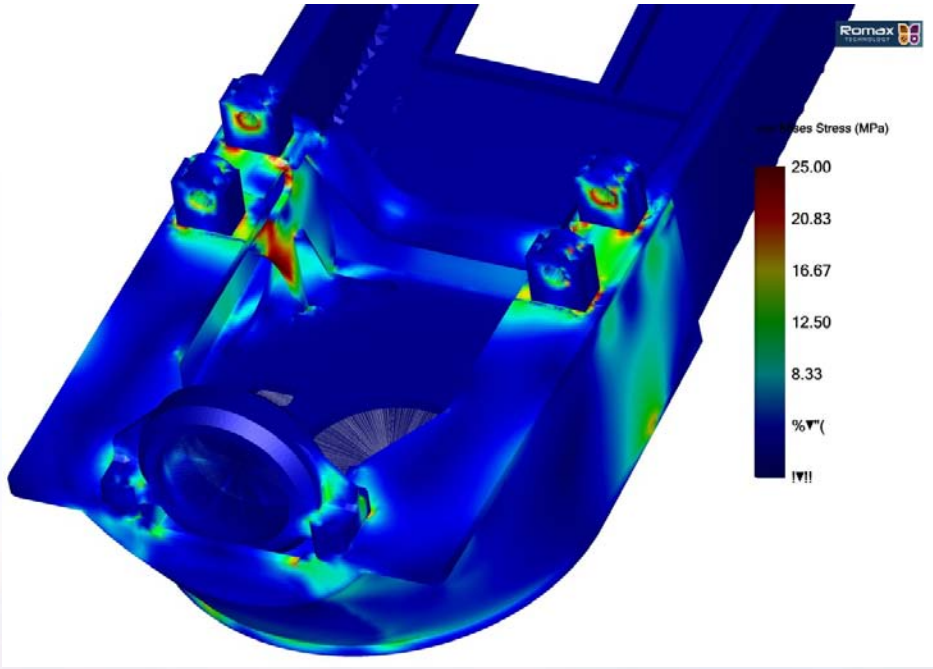
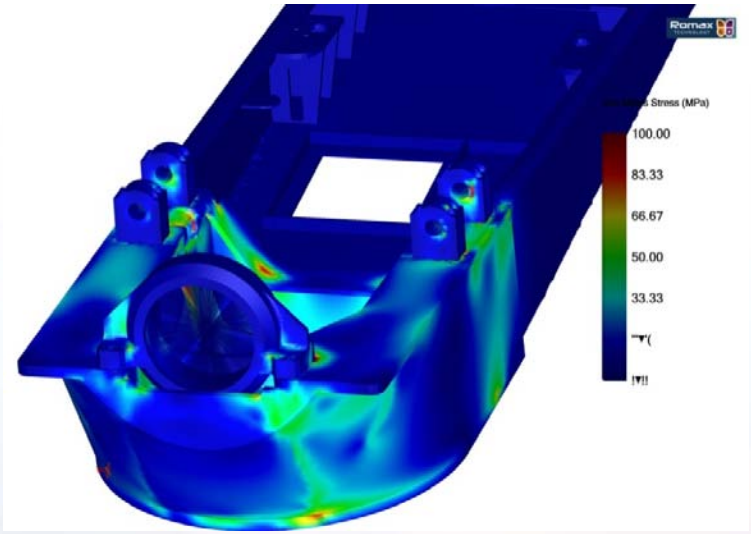
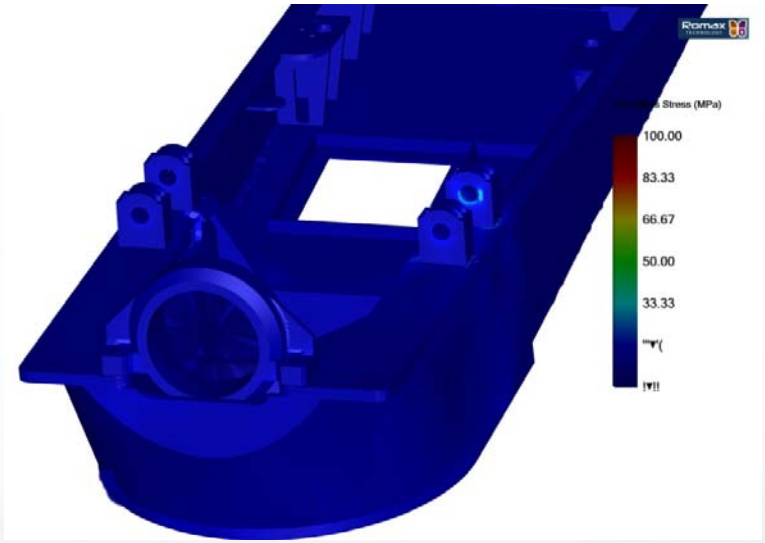


AALC

AALC Impact on Extreme Bedplate Loads - M_{yMax}



Base



AALC

Summary

- Detailed computational model of drive train utilized to examine impact of AALC on drive train components
- AALC significantly reduces the extreme loads on drive train components
  - bearing static stresses for limiting cases reduced by as much as 50%
  - fatigue damage reduced between 7 and 32% for the load carrying bearings
  - extreme load bedplate non-torque stresses reduced
- Greatest advantage for the turbine appears to be the reduction of the off-axis moments, which are often the design limiting loads for strength

Conclusions & Future Work

- **Conclusions:**
  - **AALC reduces off-axis drive train moments, which are often the design limiting loads for strength**
  - **AALC has great potential to reduce ultimate and fatigue loads throughout the drive train of a turbine**

- **Future Work:**
  - **investigate impact on fatigue damage on other drivetrain components**
  - **investigate impact of drive train damage reduction on turbine cost of energy**
  - **investigate sensitivity of results to drive train details (different main shaft, gearbox and bedplate configurations) and turbine size**

Thank You

Questions?

Sandia National Laboratories

www.uni-stuttgart.de/windenergie

University of Stuttgart
Germany

Nonlinear Model Predictive Control of Wind Turbines Using LiDAR

David Schlipf[1], Dominik Schlipf[2], Martin Kühn[3]

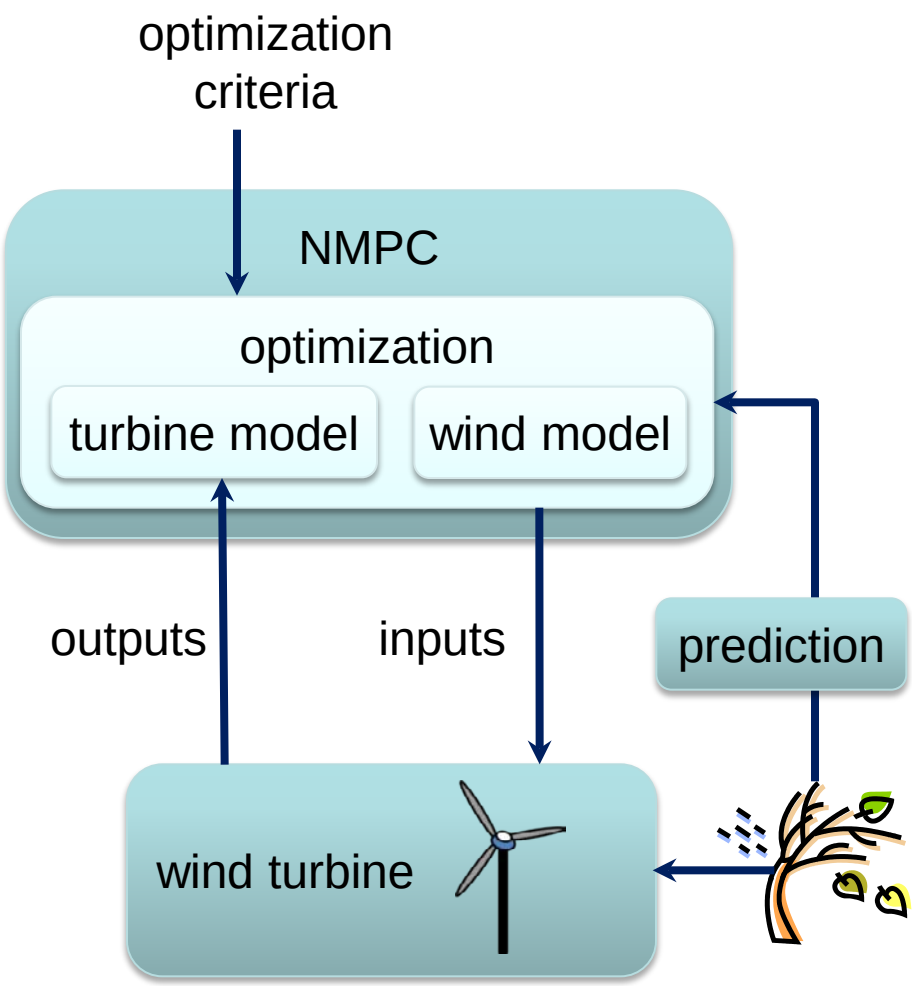
[1]Endowed Chair of Wind Energy, Universität Stuttgart

[2]Institute of Combustion and Power Plant Technology, Universität Stuttgart

[3]AG Wind Energy Systems, Universität Oldenburg

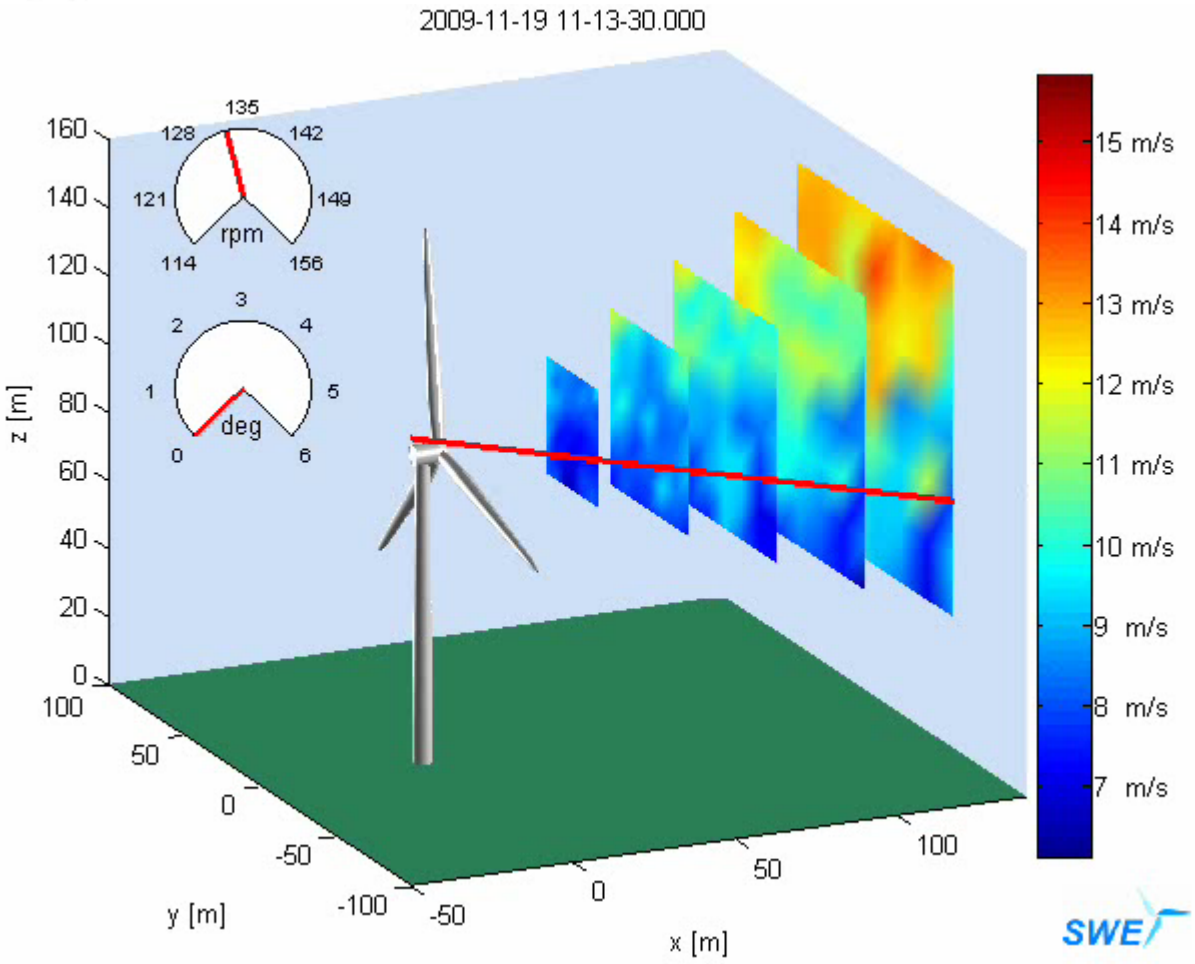
SWE Endowed Chair of Wind Energy at the Institute of Aircraft Design

Motivation NMPC



- NMPC advanced process control tool in chemical engineering
- Optimizes control inputs online
- Nonlinear and multivariable control
- Considers actuator and system constrains
- Information about important disturbance needed

Motivation LiDAR



Measurements from a 5MW turbine in 2009

First results show that LiDAR can…

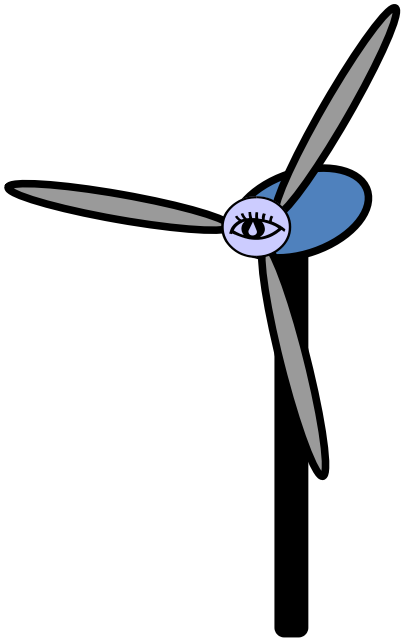
- provide preview wind information
- improve yaw control
- provide input for feed forward pitch control

NMPC and LiDAR promising combination for load reduction

[SWE]

www.uni-stuttgart.de/windenergie

Content



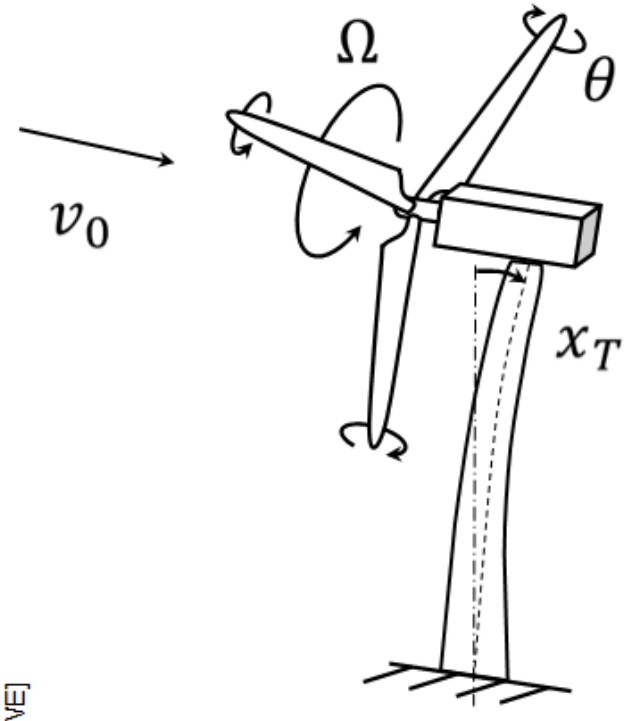
1. Modeling of the Wind Turbine
2. Controller Design
3. Simulated LiDAR Measurements
4. Results
5. Conclusion and Outlook

Modeling of the Wind Turbine

The Aeroelastic Model (FAST/Simulink)

- NREL 5MW onshore baseline turbine (16 DOFs)
- Collective pitch actuator added: 2nd-order (+1DOF)
- 3D stochastic wind input (TurbSim)

[NREL]

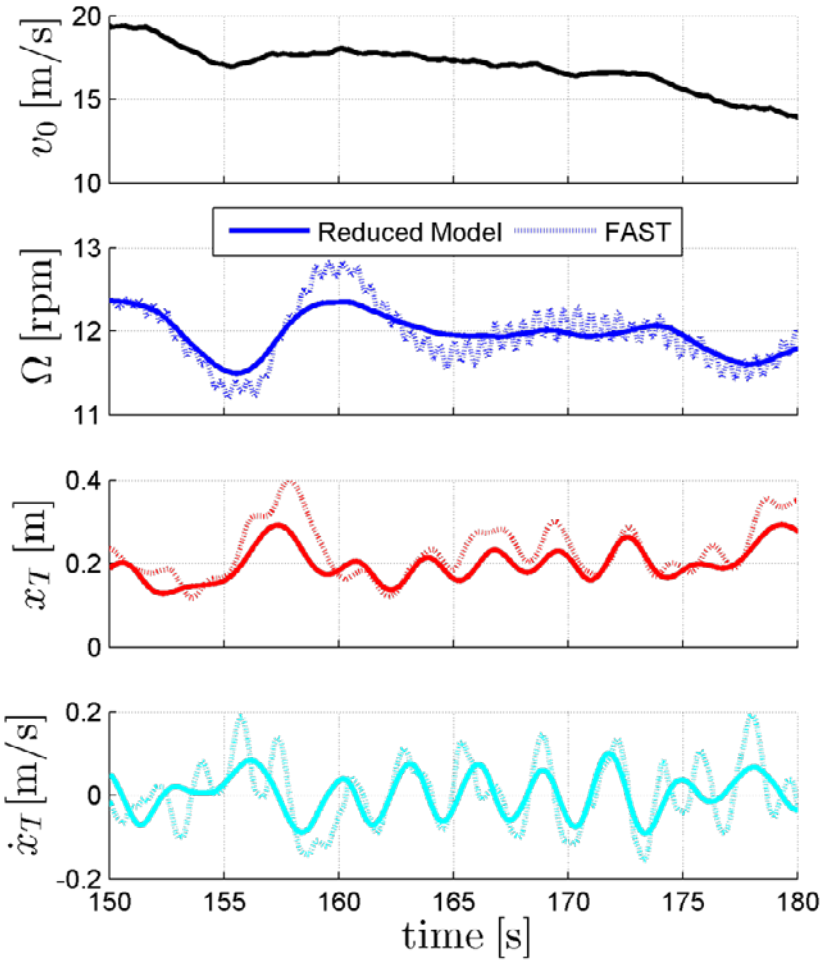


The Reduced Nonlinear Model

- 3 DOFs: 1st tower fore-aft bending, rotor motion, collective pitch actuator
- Control inputs:
  collective pitch, generator torque rate
- Rotor effective wind input

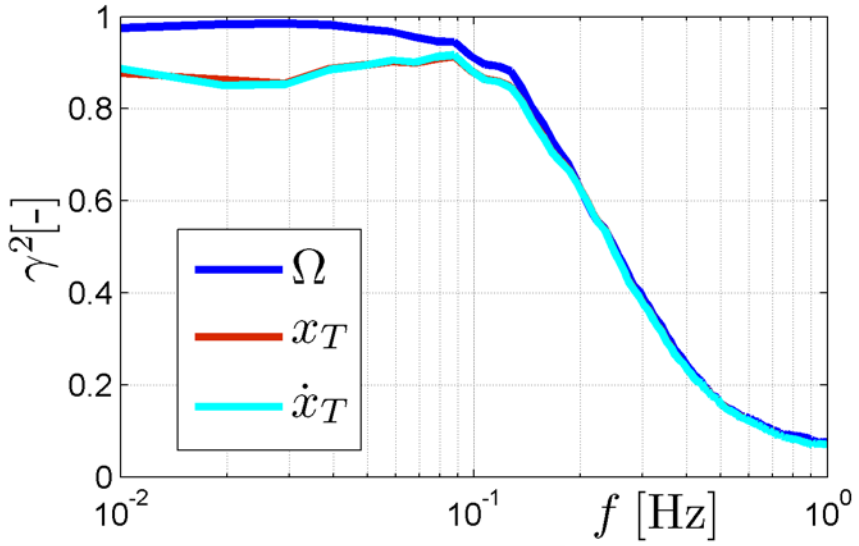
[SWE]

Modeling of the Wind Turbine - Comparison



Closed loop comparison (baseline controller)

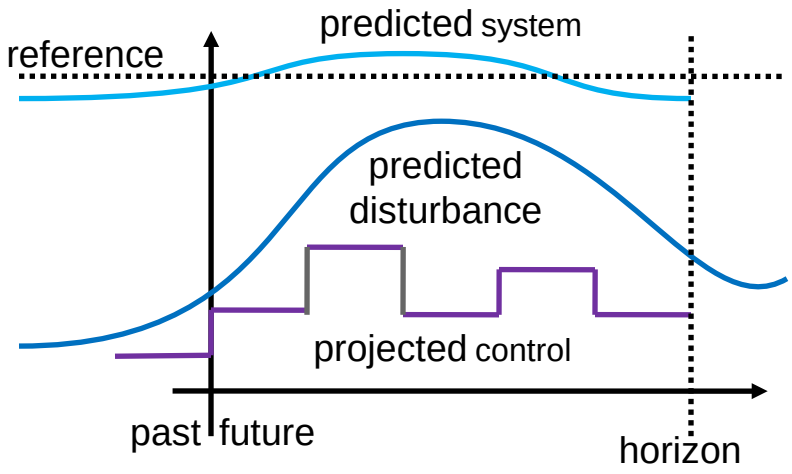
- Aeroelastic model + Turbsim
- Reduced nonlinear model + rotor effective wind speed from Turbsim
- Good correlation for rotor speed
- Coherence shows also good correlation for tower movement up to ~0.2 Hz



Reduced model suitable for collective pitch control

[SWE]

Controller Design – Principle NMPC



- Solves optimal control problem:
  Optimizes control inputs over a finite horizon
- Closed loop by iteration:
  - application of short control sequence
  - update of initial conditions

- Can handle multivariable control tasks naturally
- Considers actuator and system constrains
- Can use nonlinear models, trade-off between performance and computational effort

Controller Design – Optimal Control Problem

„less loads and more power“

↓

Optimal control problem

$$\min \int_{t_0}^{t_0+T_f} F(x)\,d\tau$$

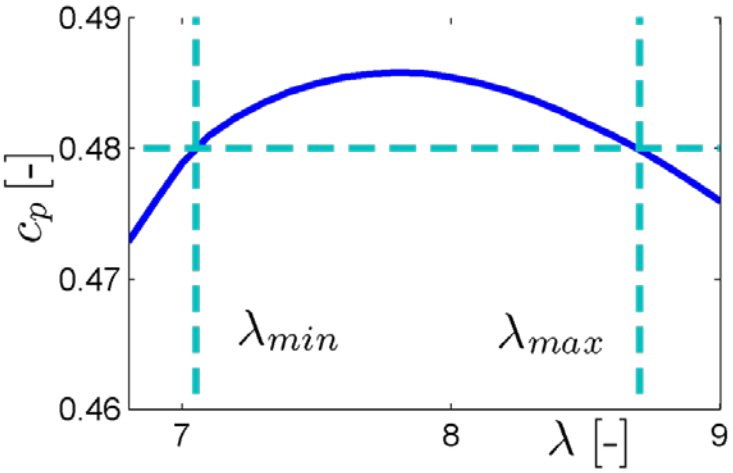
Tuning in terms of changing quantities: trade-off between

- rotor speed variation
- tower movements
- power variation above rated wind speed
- pitch variation
- generator torque variation
- pitch angle below rated wind speed

$$\begin{aligned} F(x) = {} & Q_1(\Omega - \Omega_{ref})^2 \\ & + Q_2 \dot{x}_T{}^2 \\ & + Q_3(P - P_{rated})^2 \ \forall \ (v > v_{rated}) \\ & + R_1 \dot{\theta}^2 \\ & + R_2 \dot{M}_{gen}{}^2 \\ & + R_3 \theta^2 \ \forall \ (v < v_{rated}) \end{aligned}$$

[SWE]

Controller Design – Optimal Control Problem



$$\min \int_{t_0}^{t_0+T_f} F(x)d\tau$$

such that:

Constrains

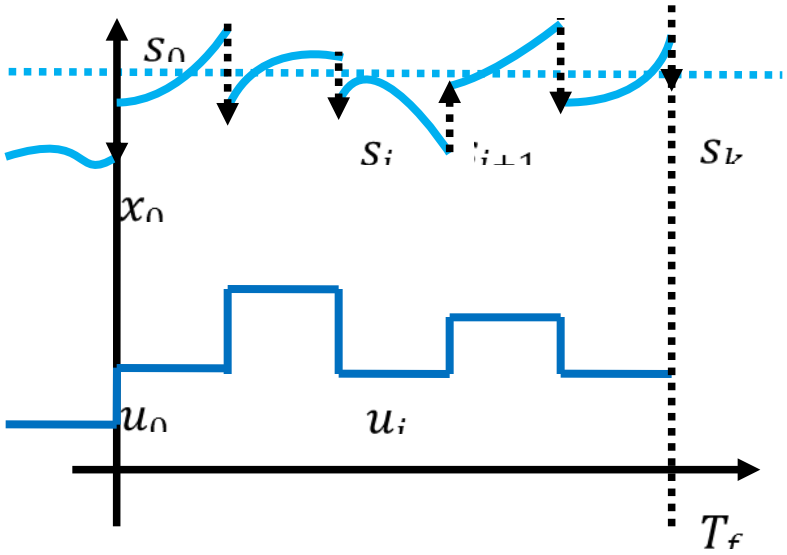
- pitch variation
- generator torque variation

$$\left|\dot{\theta}\right| \leq \dot{\theta}_{max}$$
$$\left|\dot{M}_{gen}\right| \leq \dot{M}_{gen,max}$$

- rotor speed variation
- tip speed ratio below rated wind speed

$$\Omega \leq 1.2\,\Omega_{rated}$$
$$\lambda_{min} \leq \lambda \leq \lambda_{max}\ \forall\ (v < v_{rated})$$

Controller Design – Direct Multivariable Shooting



optimal control problem

↓ Direct Multivariable Shooting

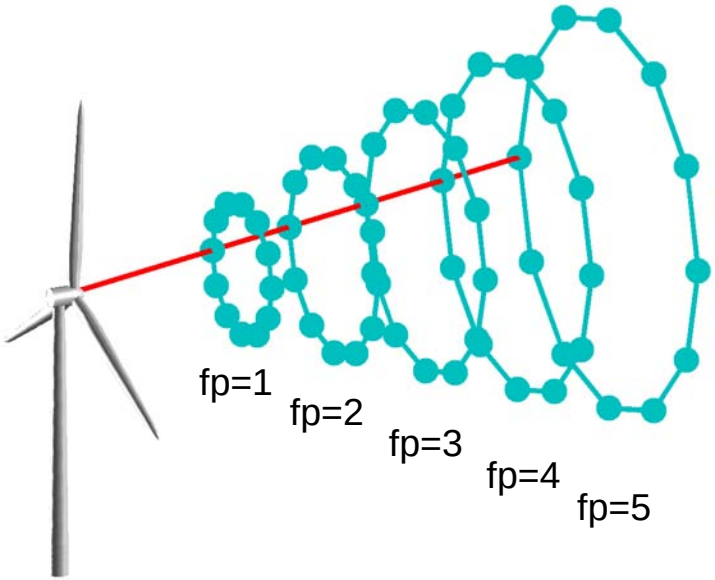
nonlinear program

↓ Sequential Quadratic Programming

quadratic program

Usage of open source HQP
a solver for sparse nonlinear optimization

LiDAR Measurements - Simulation



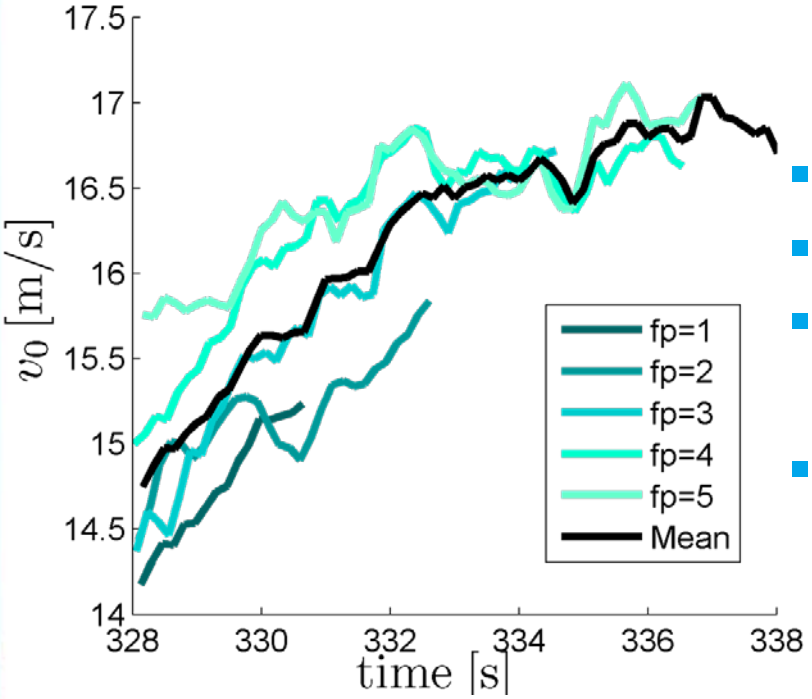
Simulation of a real system

- Pulsed system with scanner
- 12 points in 5 cycles every 2s

- Line-of-sight wind speed
- Volumetric measurement
- Taylor's Hypothesis is used

Realistic scanning of the stochastic wind field used in the aeroelastic simulation

LiDAR Measurements - Processing

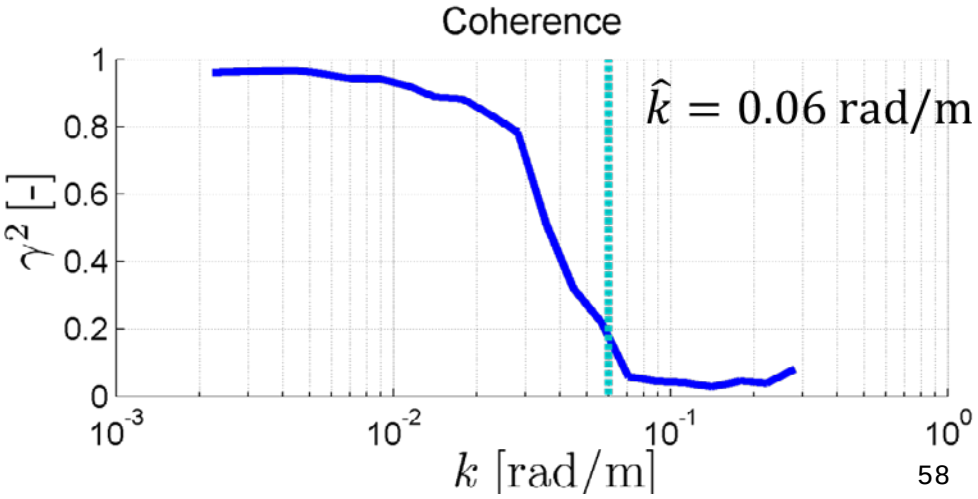


- Direction corrected assuming perfect alignment
- Moving average over each circle
- Combined to one rotor averaged wind speed

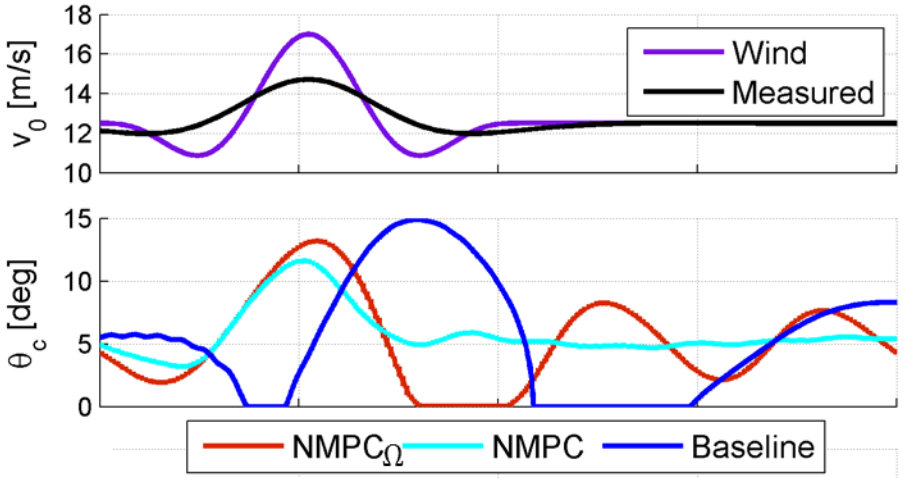
- Filter depending on mean wind speed to use only those frequencies which have been detected by real measurements

Correlation LIDAR • Turbine

$$f_{cutoff} = \frac{\hat{k}\bar{u}}{2\pi} \approx 0.03 - 0.24Hz$$



Results – Extreme Loads



- Reference: baseline controller [NREL]
- Extreme operating gust (IEC) at 12.5 m/s
- Gust smoothed through spatial and temporal filter effects
- NMPC$_\Omega$: tower base bending moment still high, when only penalizing rotor speed
- NMPC: tower base bending moment reduced by 58% on maximum value, when penalizing tower velocity
- Controller uses generator torque to slow down rotor speed (MIMO)

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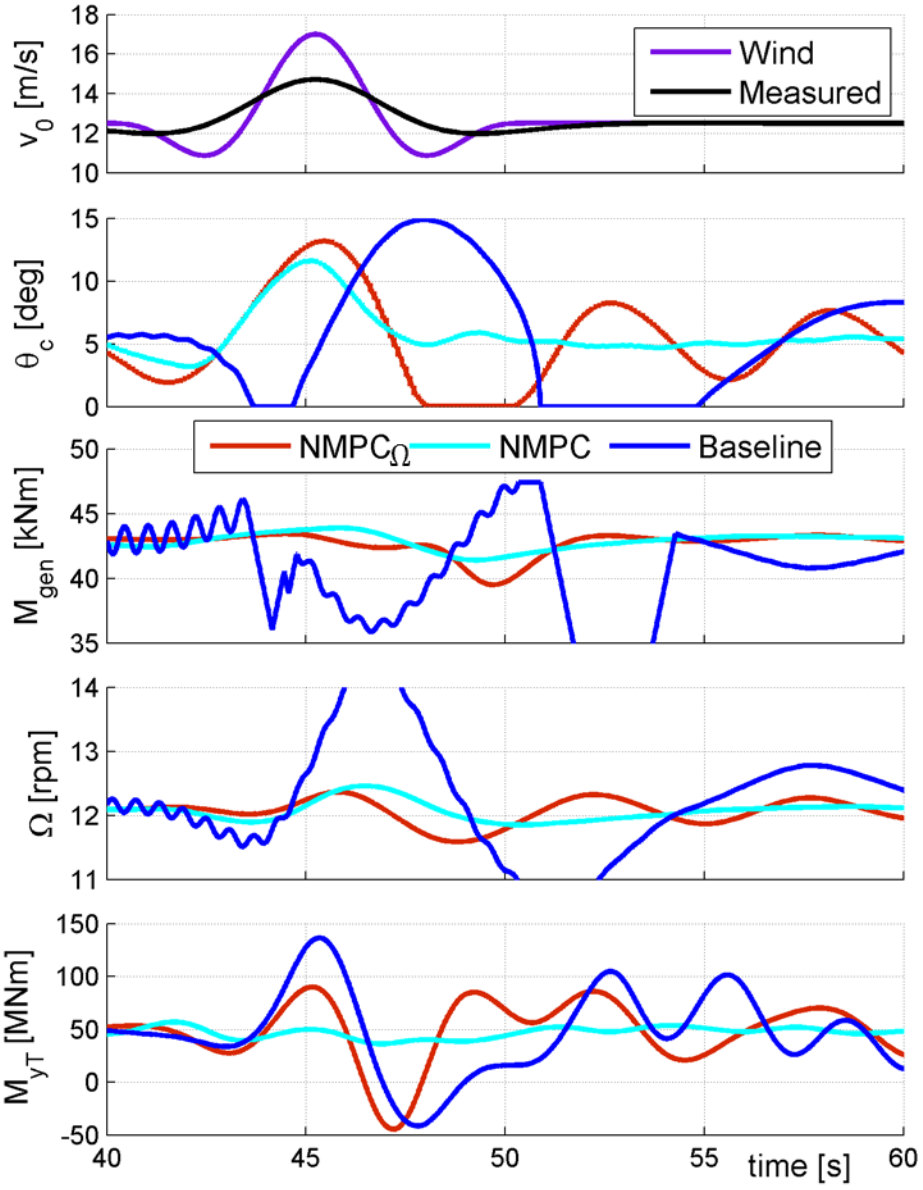

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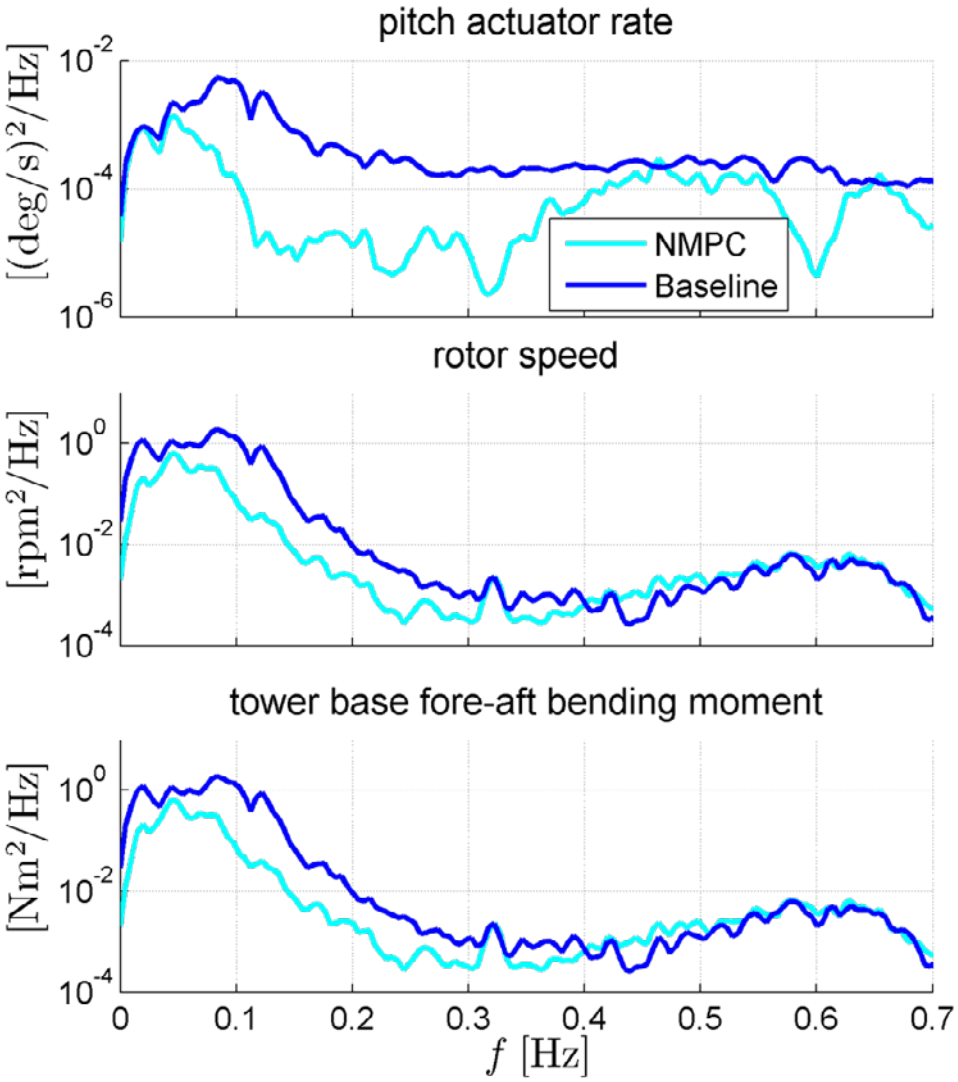
Results – Fatigue Loads



- Significant reduction in frequency domain, where wind can be predicted

Detailed fatigue load analysis

- IEC Design load case 1.2
- Turbulence class A
- Rayleigh distribution A=12 m/s

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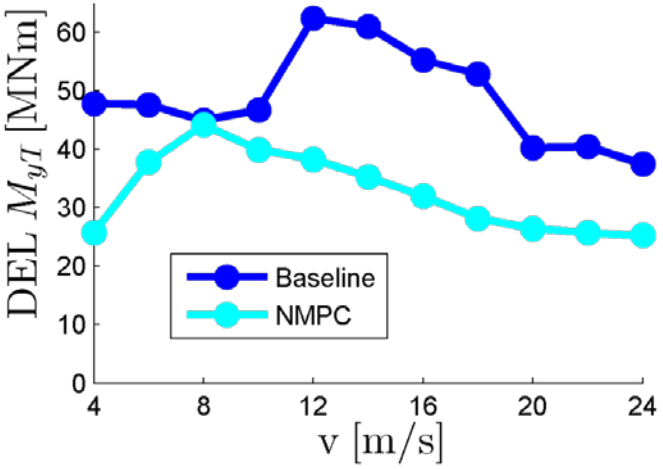
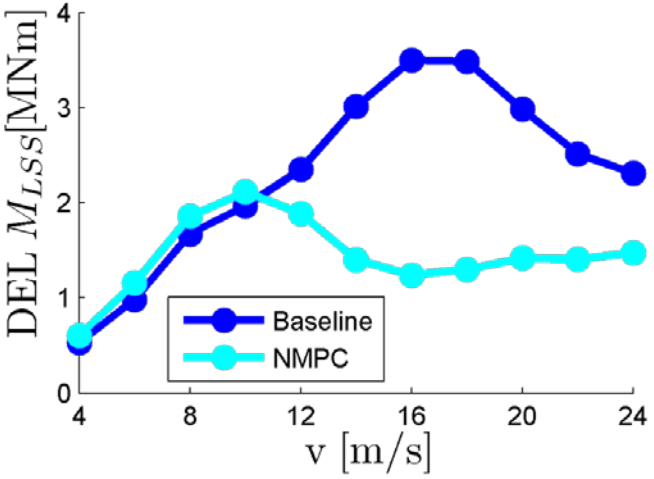
Results – Fatigue Loads

Tower base fore-aft bending moment

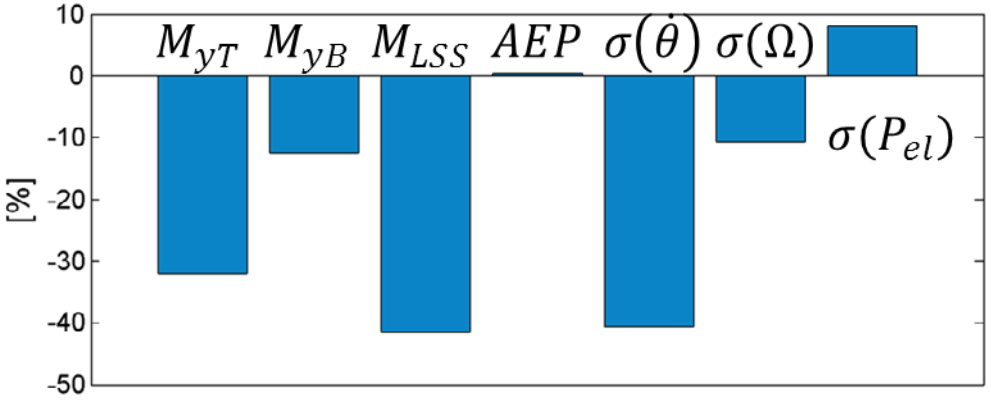


Low speed shaft torque



Tuning for load and pitch action reduction:

- Overall high load reduction on tower (M_{yT}), blades (M_{yB}) and shaft (M_{LSS})
- standard deviation of pitch speed $\sigma(\dot{\theta})$ and rotor speed $\sigma(\Omega)$ reduced
- Small increase in AEP (+0.30%)
- Increase of power fluctuation $\sigma(P_{el})$



Relative Reduction of DEL (20 years lifetime N=2E06)

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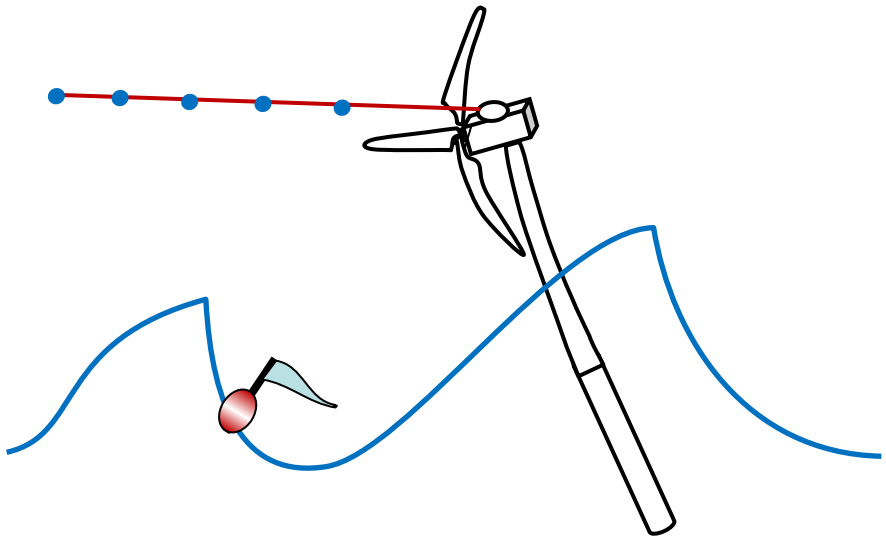
Conclusions

- NMPC with realistic simulation of a LiDAR system over full operation introduced
- Controller coordinates both generator torque and collective pitch
- Low frequencies detection of wind disturbance sufficient
- High fatigue and extreme load reduction on tower, blades and shaft
- Reduction of rotor speed variation and pitch activity
- not yet real-time (factor ~6 on PC)

SWE Outlook

- Coupling with GH Bladed and comparison to feed forward controller and advanced controller of the European UpWind project
- Comparison with linear and multilinear model predictive control
- Implementation for floating wind turbines using LiDAR and buoys
- Learning from new offshore measurements:
  two scanning LiDAR system actually installed on alpha ventus



Thanks for you attention!

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Acknowledgement

This research is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in the framework of the German joint research project “LIDAR II - Development of nacelle-based LIDAR technology for performance measurement and control of wind turbines”.

WindForS

The Southern German Wind Energy Research Alliance

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Questions and Answers