Structural Analysis Tools and Concepts for Rotor Blades with Morphing Trailing Edge

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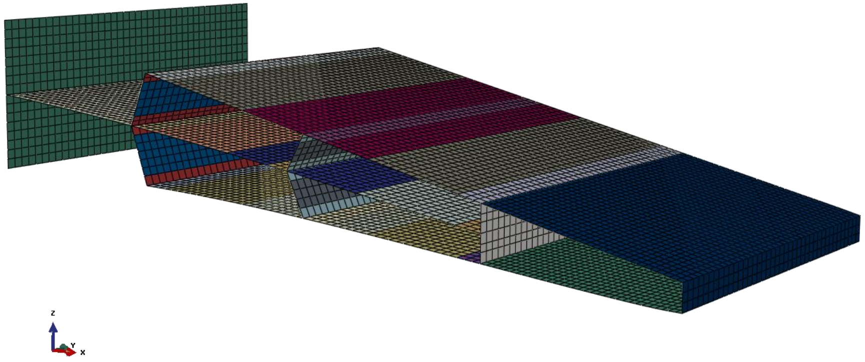
Anforderungen, Möglichkeiten, Nutzen, 20.09.2016, DLR Braunschweig

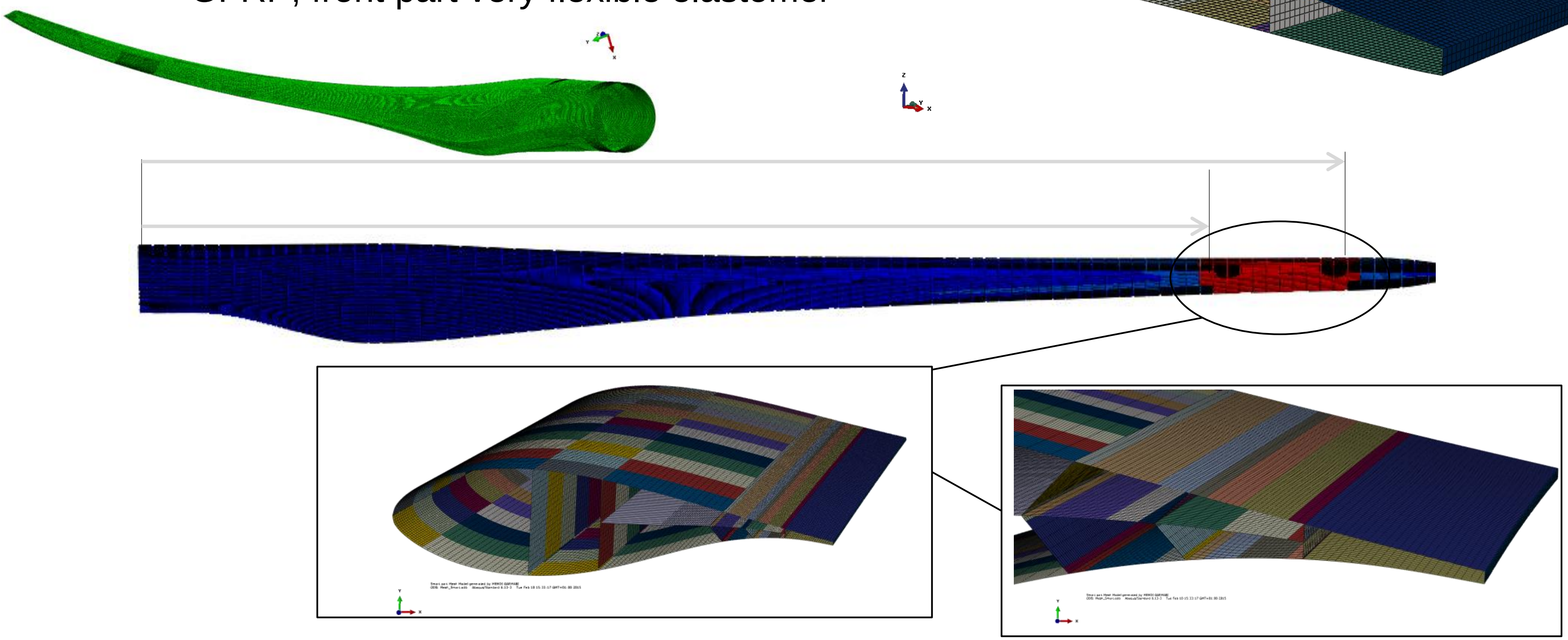
Overview

- Introduction
  - Rotor blades with morphing trailing edge
- Tools for evaluating the structural effectiveness
  - Tools for Finite Element Analysis
  - Aeroelastic coupling
  - Fatigue analysis
  - Stress analysis
- Providing alternative structural concepts
  - Multi-stable components
- Concluding remarks

Introduction
Smart Rotor Blades: Morphing Trailing Edge

- Project Smart Blades: Load alleviation using active trailing edge
  - Morphing mechanism designed by DLR, flexible GFRP mid-plane, back part skins GFRP, front part very flexible elastomer





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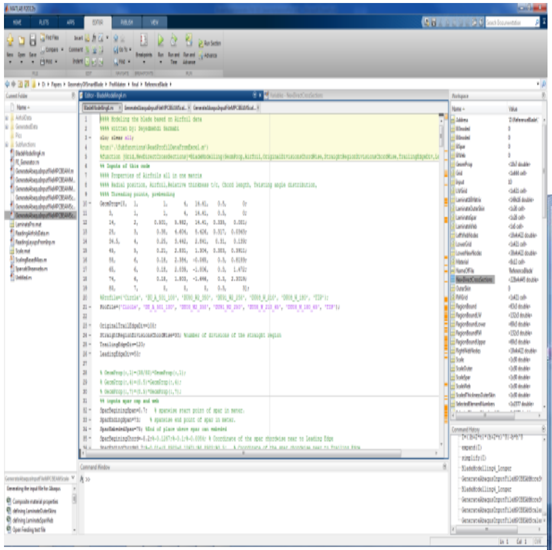
Tools for Finite Element Analysis

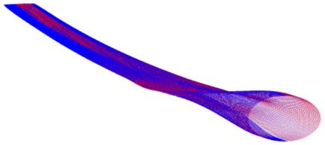
- MATLAB Code -> input file for Abaqus for 3-D FE model (shell elements)
- Parametric: Geometry/stiffness data (data of components, dimensions, composite lay-up) and FE mesh density are parameterized.
- Optimization of structural properties

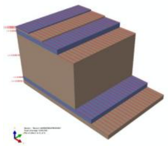
Rotor Blade FE Model Generator
input=*.txt *.xls
output= *.inp

Abaqus Solver
Input= *.inp
Output= *.odb

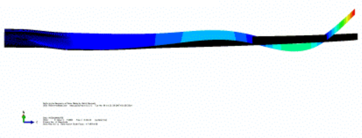
Abaqus Viewer
input= *.odb



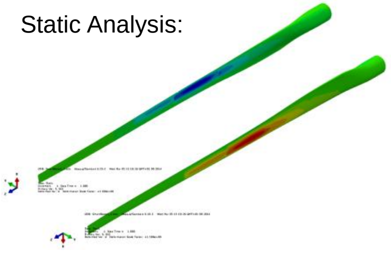




Modal Analysis

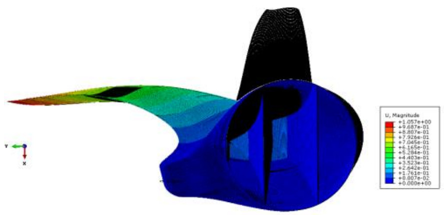


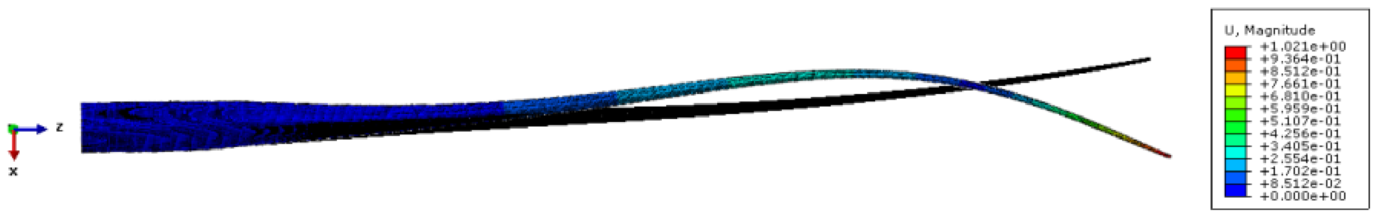
Static Analysis:

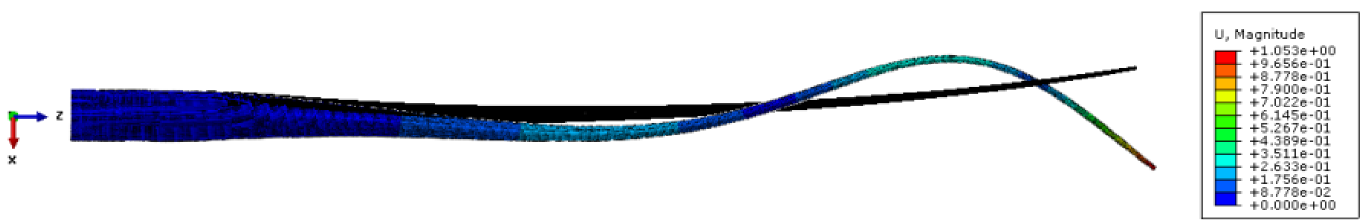


Finite Element Analysis: vibration analysis results

- **Mode shapes of 80 m blade:**

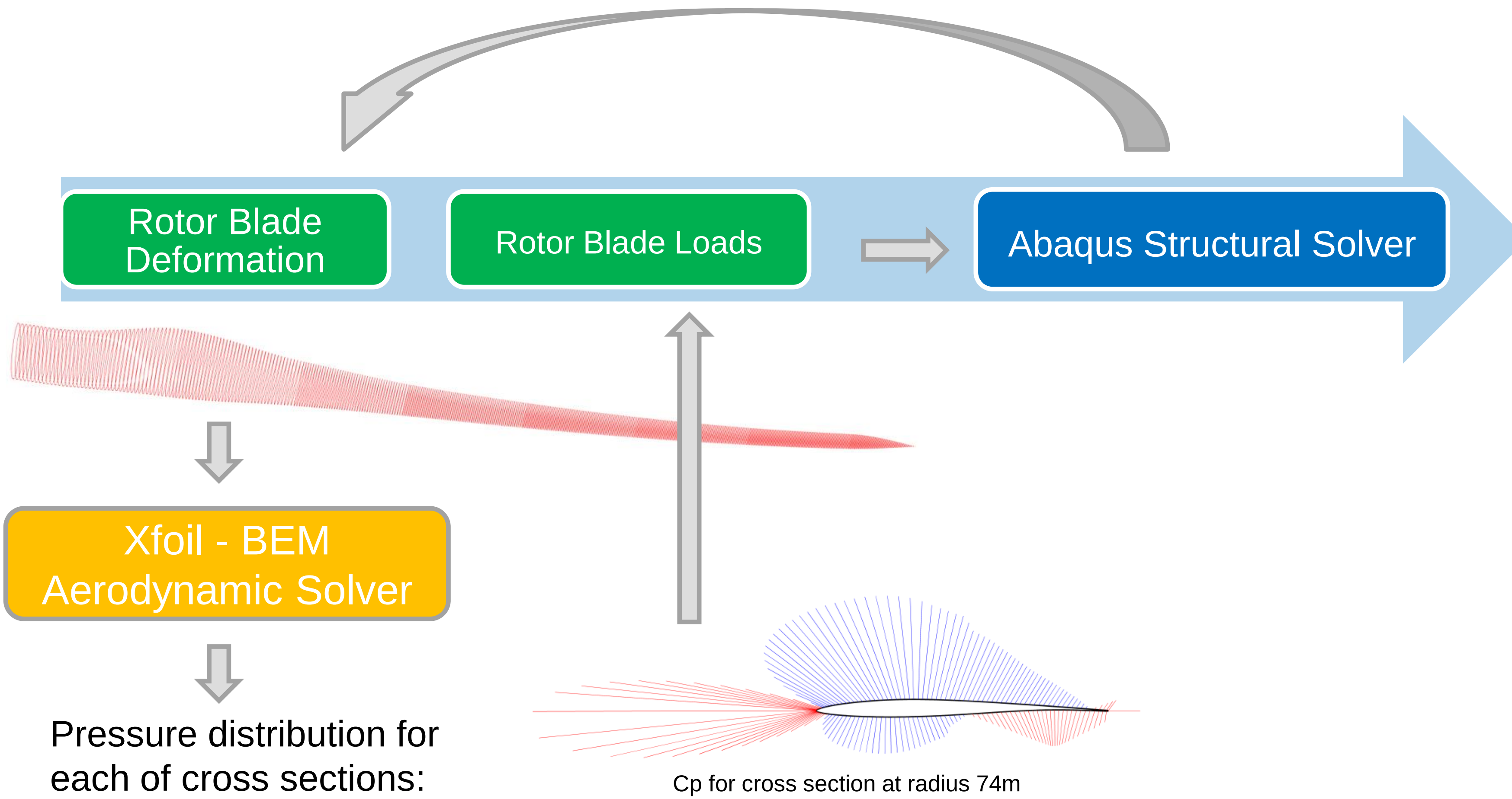




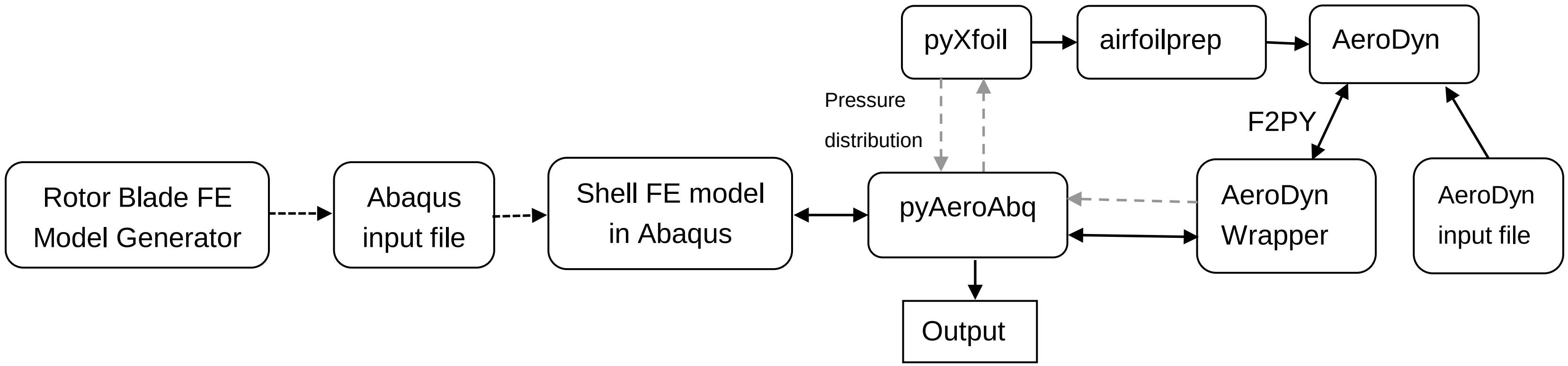


Dynamic Analysis - Aeroelastic coupling

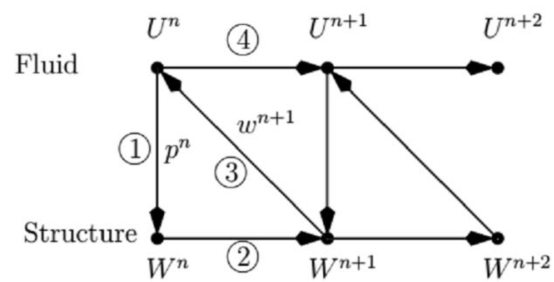
- Aerodynamic loads: 2-way coupling for structure – aerodynamics (Garmabi et al.)



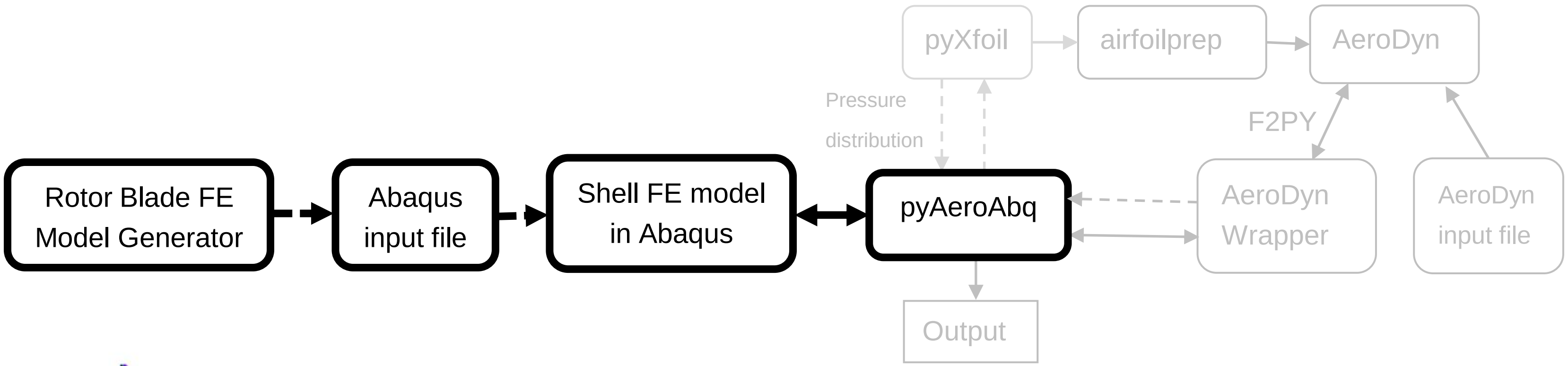
Aeroelastic coupling (1):
Coupling the tools: Abaqus, AeroDyn and Xfoil

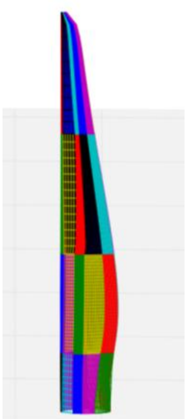


Time marching procedure in coupling approach:

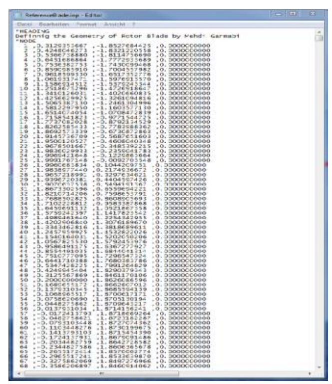


Aeroelastic coupling (2): Generating a shell FE model of a rotor blade

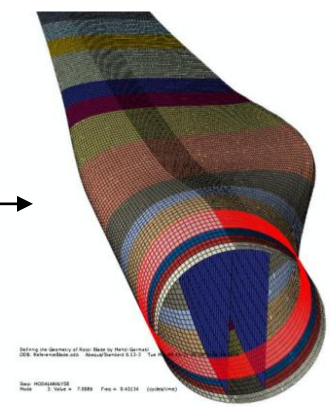




pyBlade

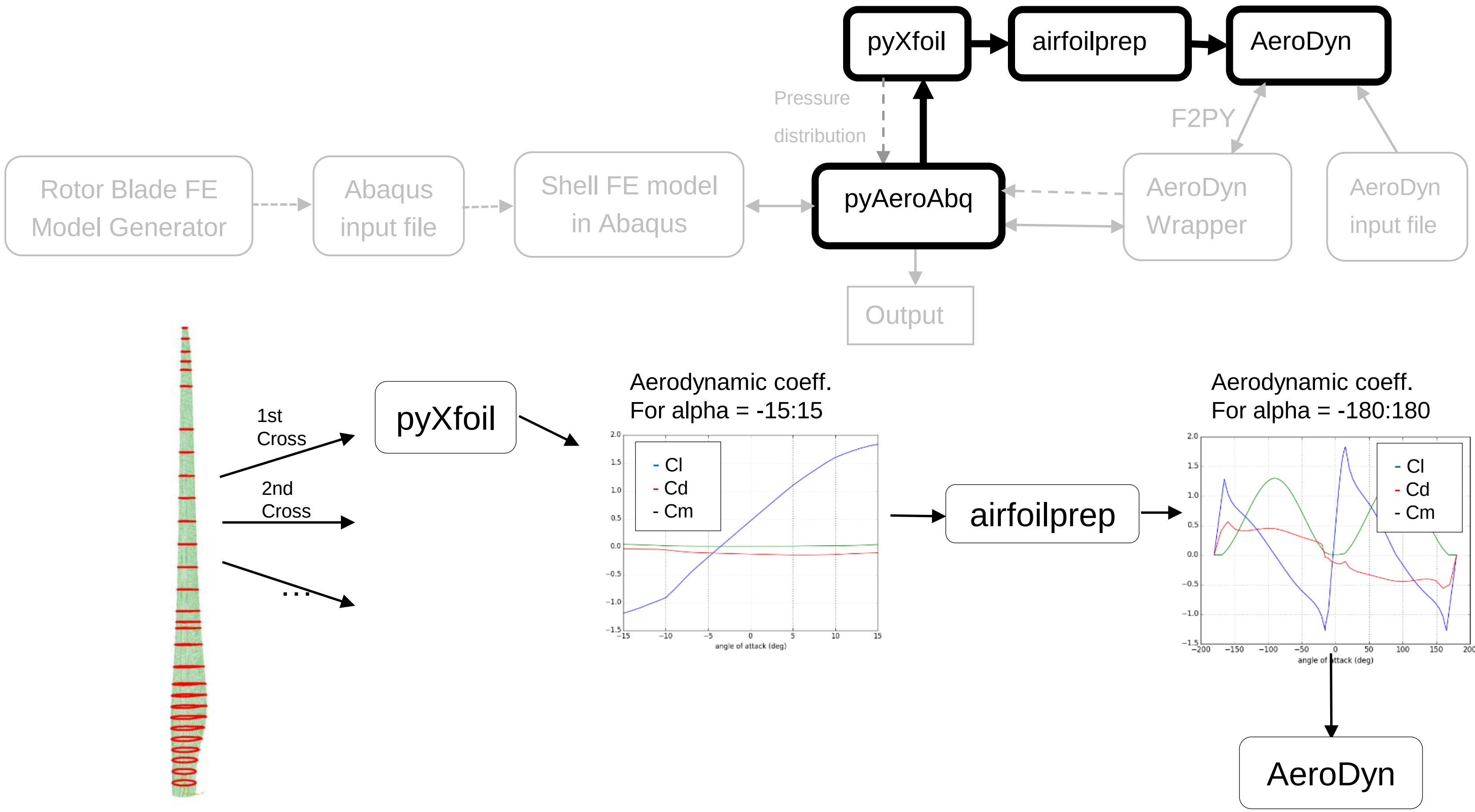


Abaqus input file

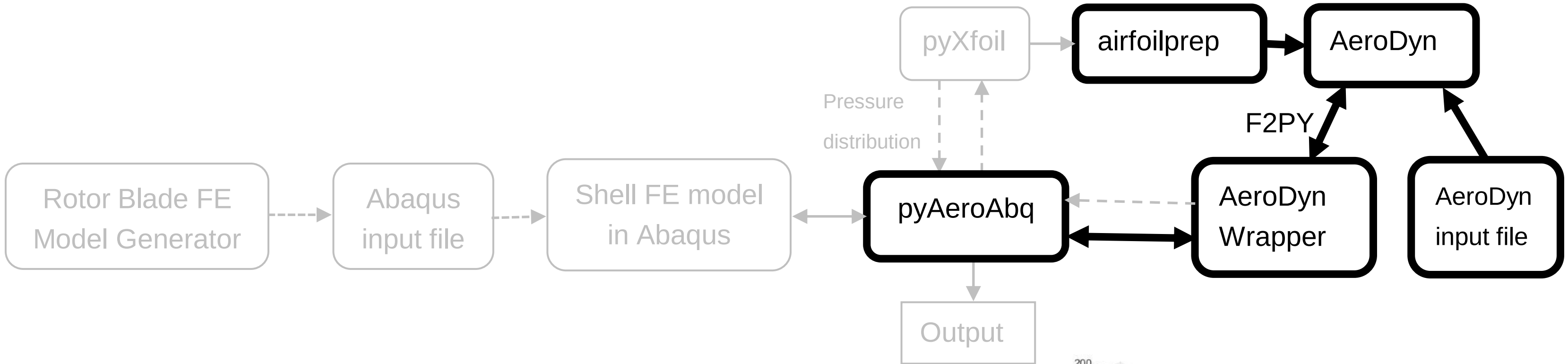


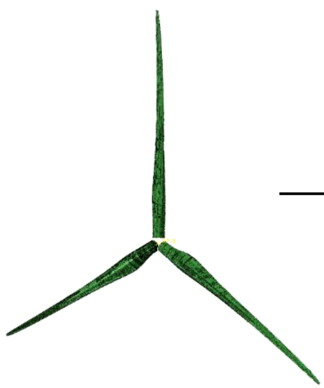
Shell FE model in Abaqus

Aeroelastic coupling (3):
Determining the aerodynamic coefficients

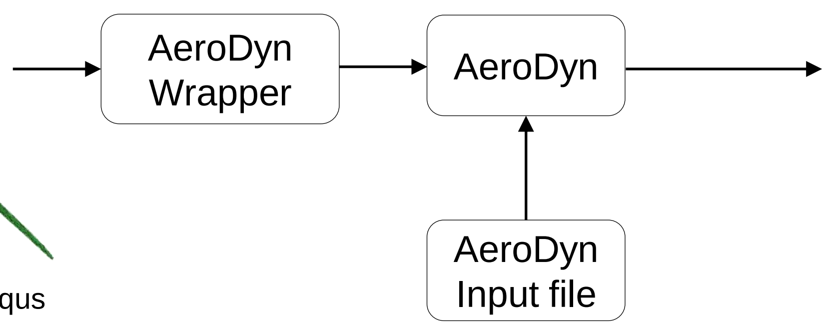


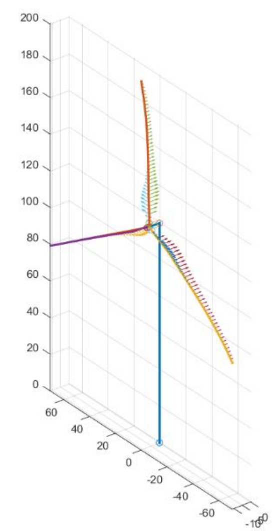
Aeroelastic coupling (4): Determining the aerodynamic loads using AeroDyn





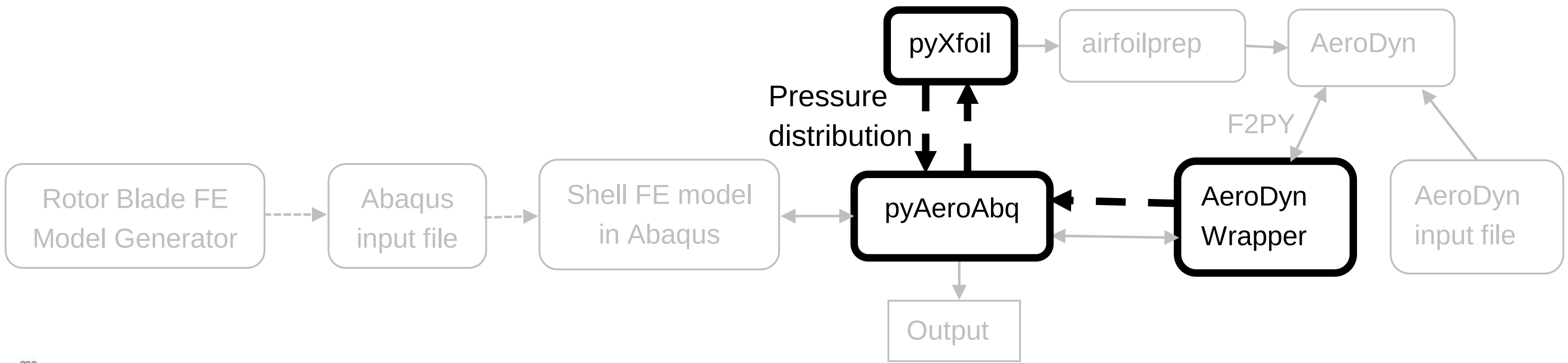
Rotor model in Abaqus

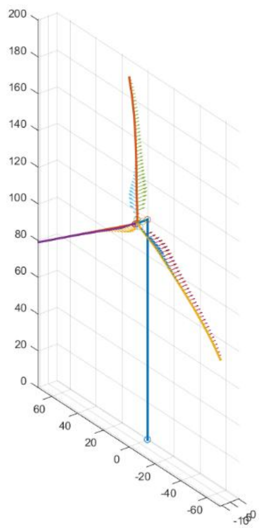




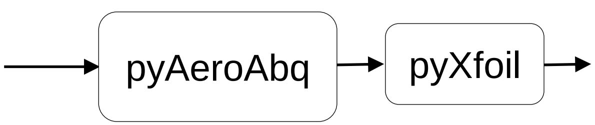
Aerodynamic loads

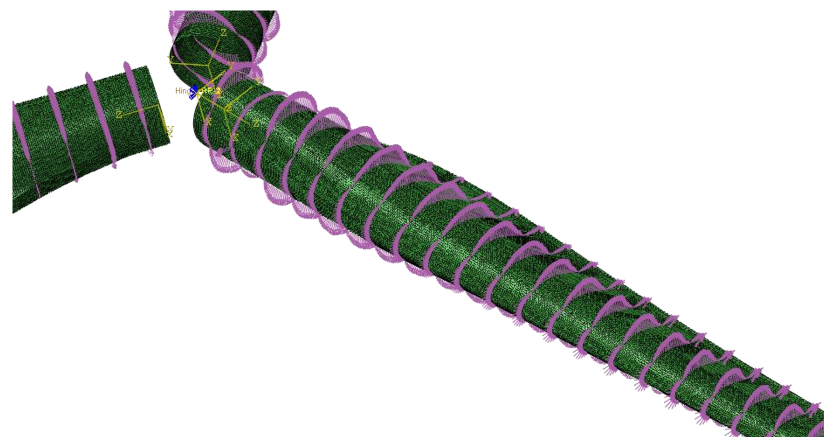
Aeroelastic coupling (5): Determining the pressure distribution around the blades





Aerodynamic loads





Pressure distribution

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Fatigue Damage Model (1): Basics

Including fatigue modeling in FE structural analysis (Krüger, 2012; Krüger and Rolfes, 2015)

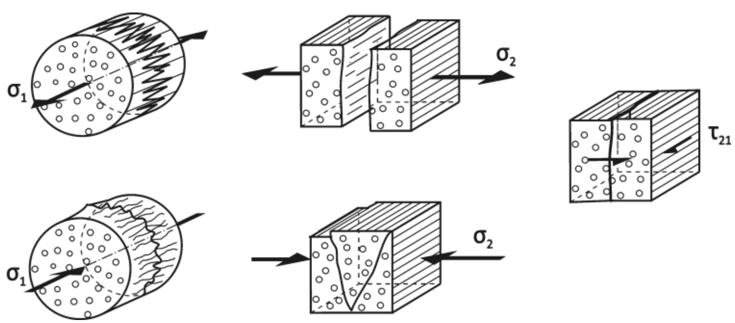
Input:

- Mechanical Model (Material, Geometry)
- External loads (Maxima, Minima)
- Number of cycles (n_i)

Analysis (FDM)

Result (2D):

- Fatigue strains: ε_i^{fat}
- Stiffness degradation: $\eta_{E1}^{t}, \eta_{E1}^{c}, \eta_{E2}^{t}, \eta_{E2}^{c}, \eta_{E21}$
- Strength degradation: $\eta_{R1}^{t}, \eta_{R1}^{c}, \eta_{R2}^{t}, \eta_{R2}^{c}, \eta_{R21}$



Strength failure of composites [cf. Puck, 1996]

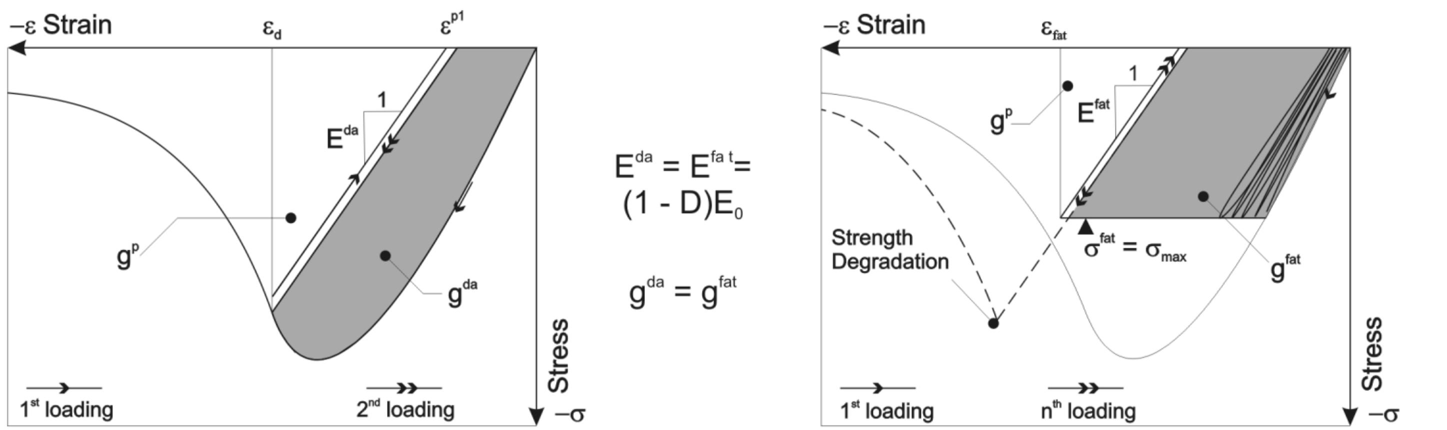
Degraded stiffness and strength:

$E_{i,D} = \eta_{Ei}\, E_{i,0};\quad \eta_{Ei}\ [0;1]$

$R_{i,D} = \eta_{Ri}\, R_{i,0};\quad \eta_{Ri}\ [0;1]$

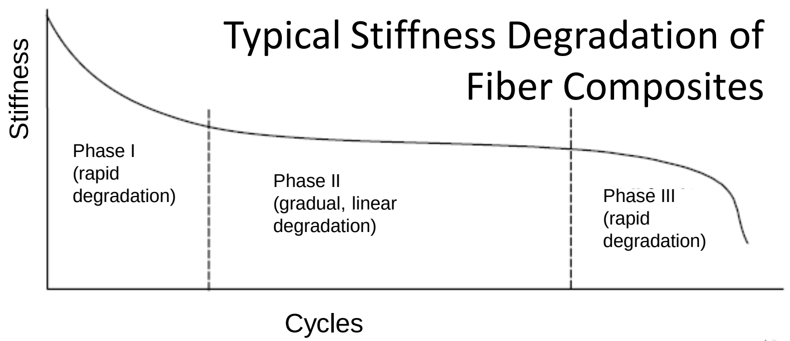
Fatigue Damage Model (2): Basic hypothesis

Continuous degradation according to Pfanner's fatigue limit hypothesis:
The damage state of a quasi-statically loaded material and that of a cyclically loaded material are comparable, if the amount of dissipated energy is equal.



Benefits:

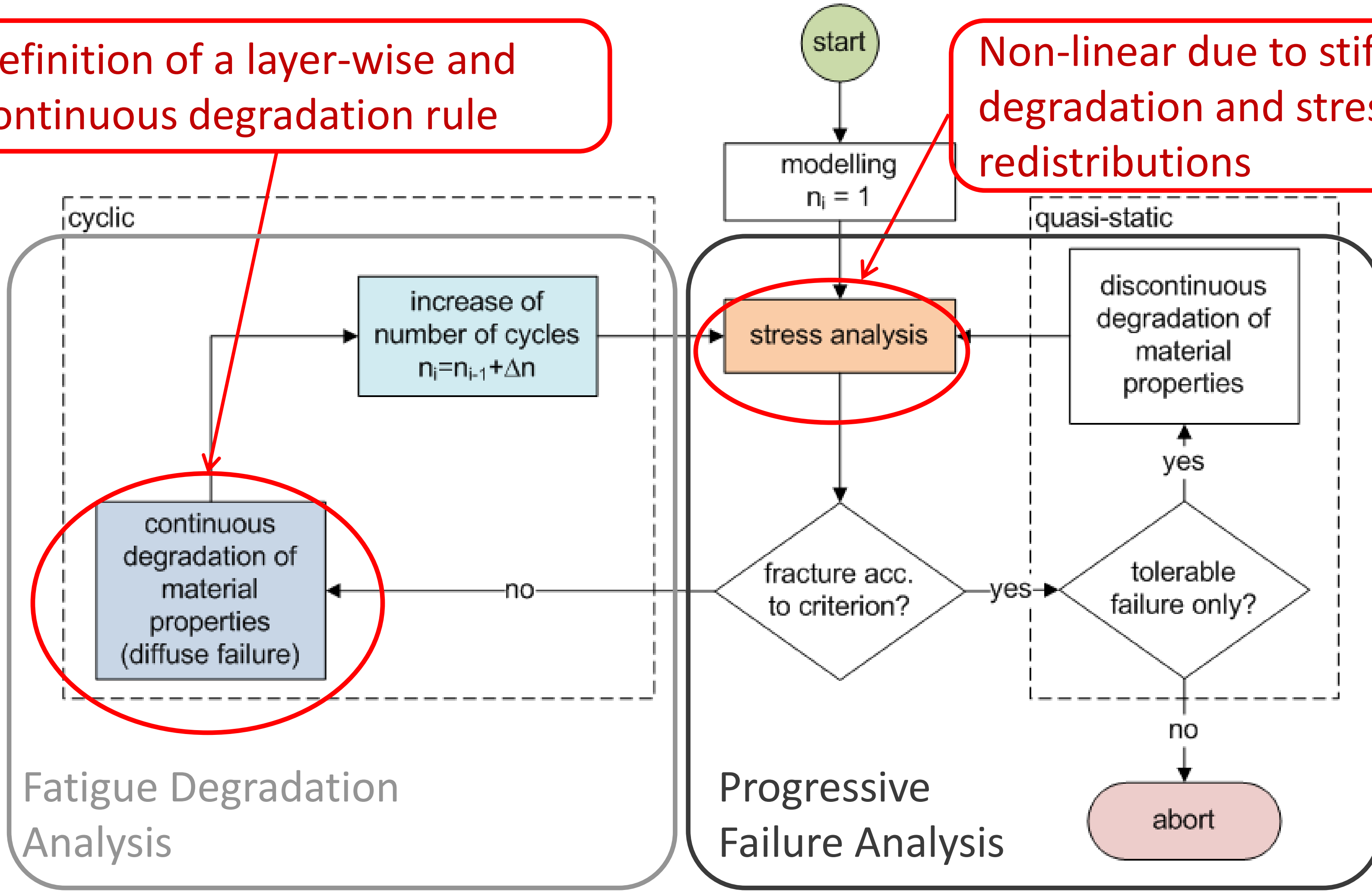
- Non-linear Damage Accumulation
- Stiffness and Strength Degradation



Fatigue Damage Model (3): Overview of procedure

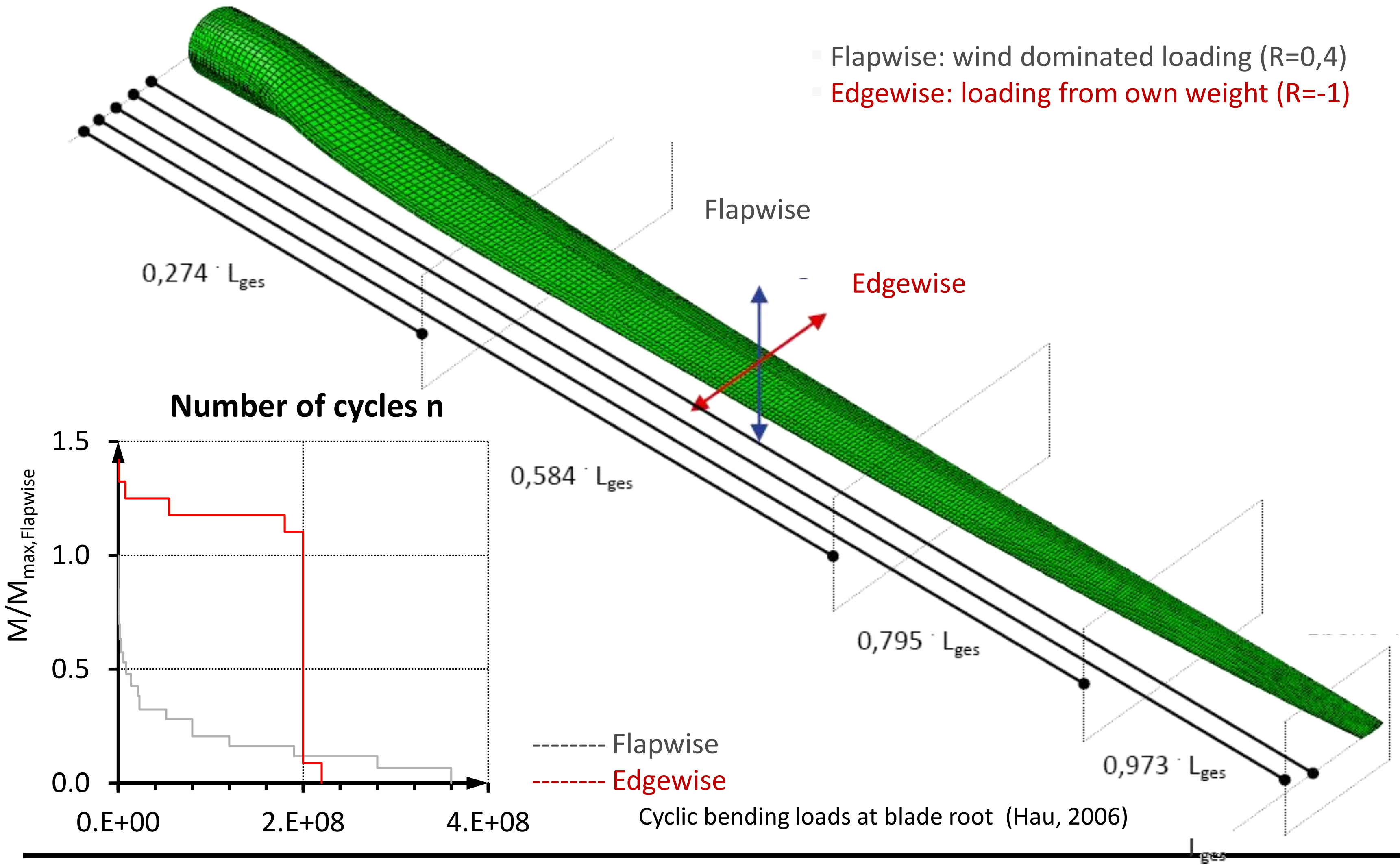
Definition of a layer-wise and continuous degradation rule

Non-linear due to stiffness degradation and stress redistributions



Fatigue Damage Model (4): Rotor blade analysis

- Flapwise: wind dominated loading (R=0,4)
- Edgewise: loading from own weight (R=-1)

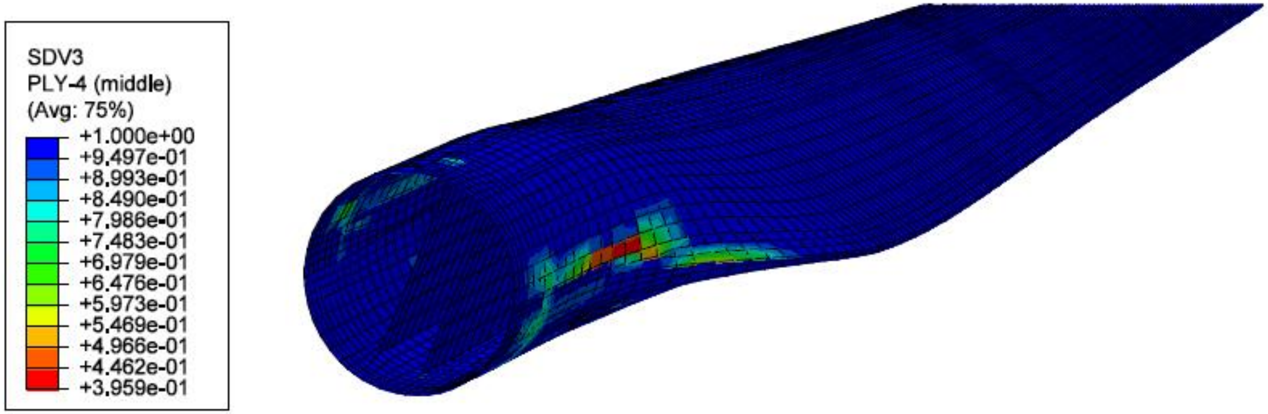


Cyclic bending loads at blade root (Hau, 2006)

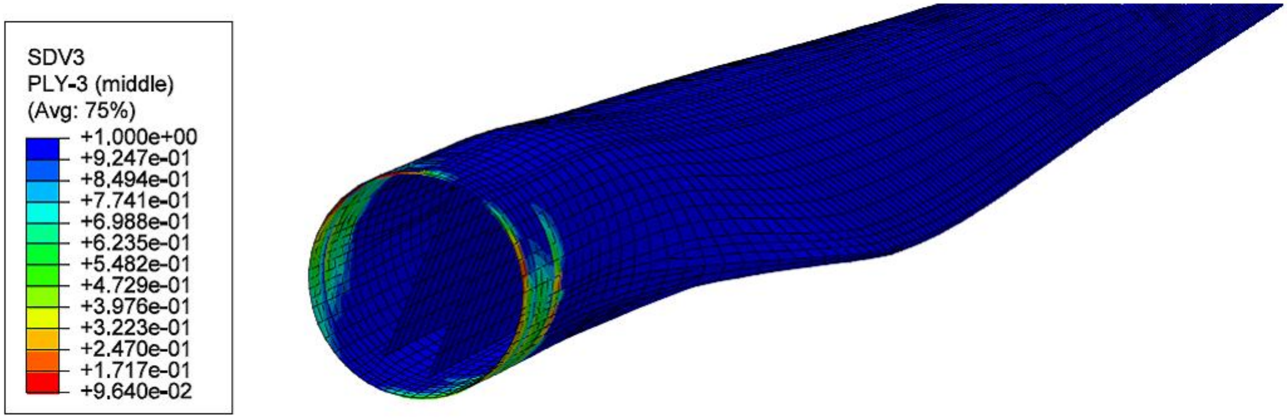
Fatigue Damage Model (5): Results

Transverse tension stiffness degradation factor η_{E2}^{t}

0° -layer (Fibre direction parallel to blade longitudinal axis)



90° -layer (Fibre direction in circumferential/transverse direction)



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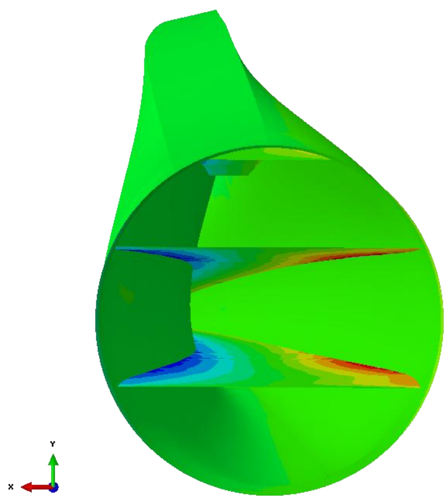
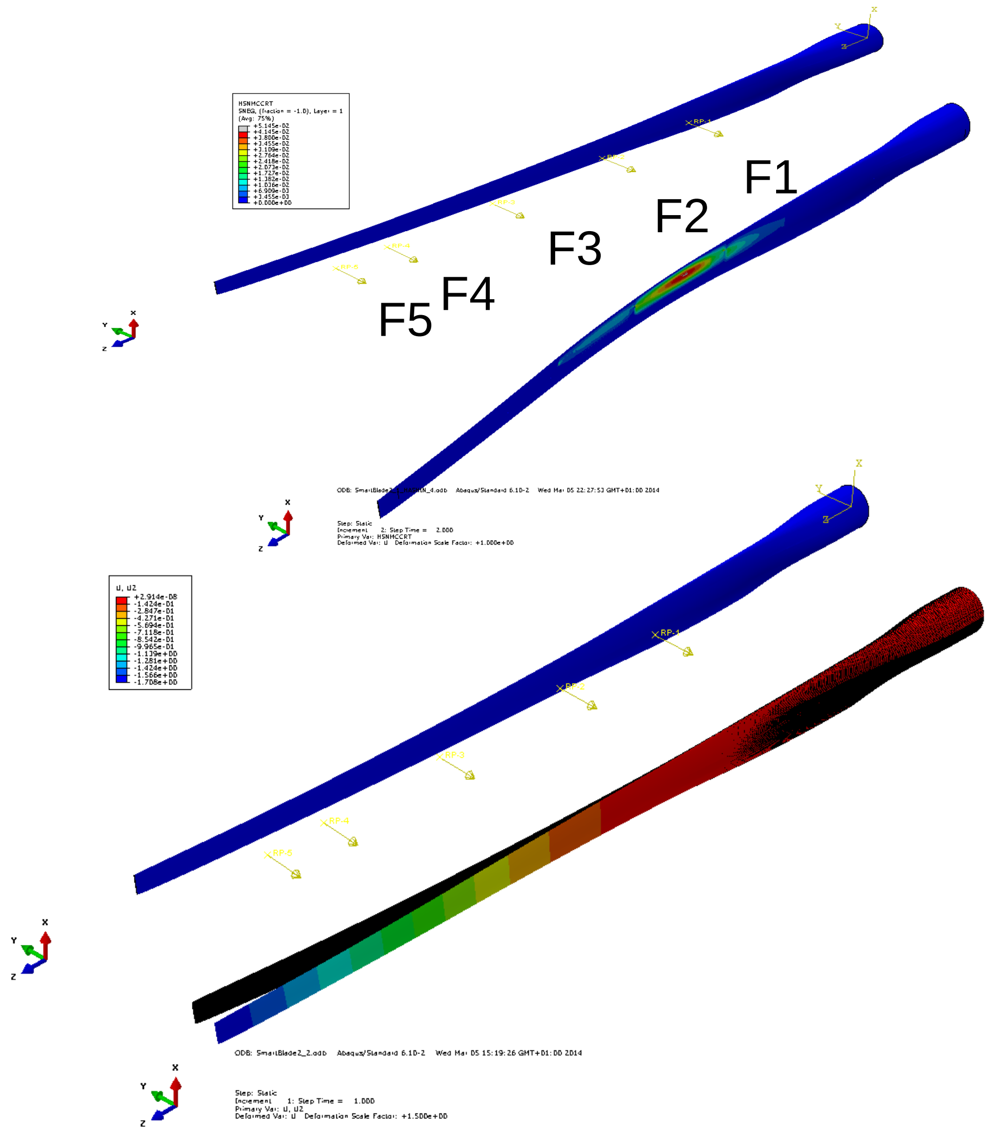
Stress analysis

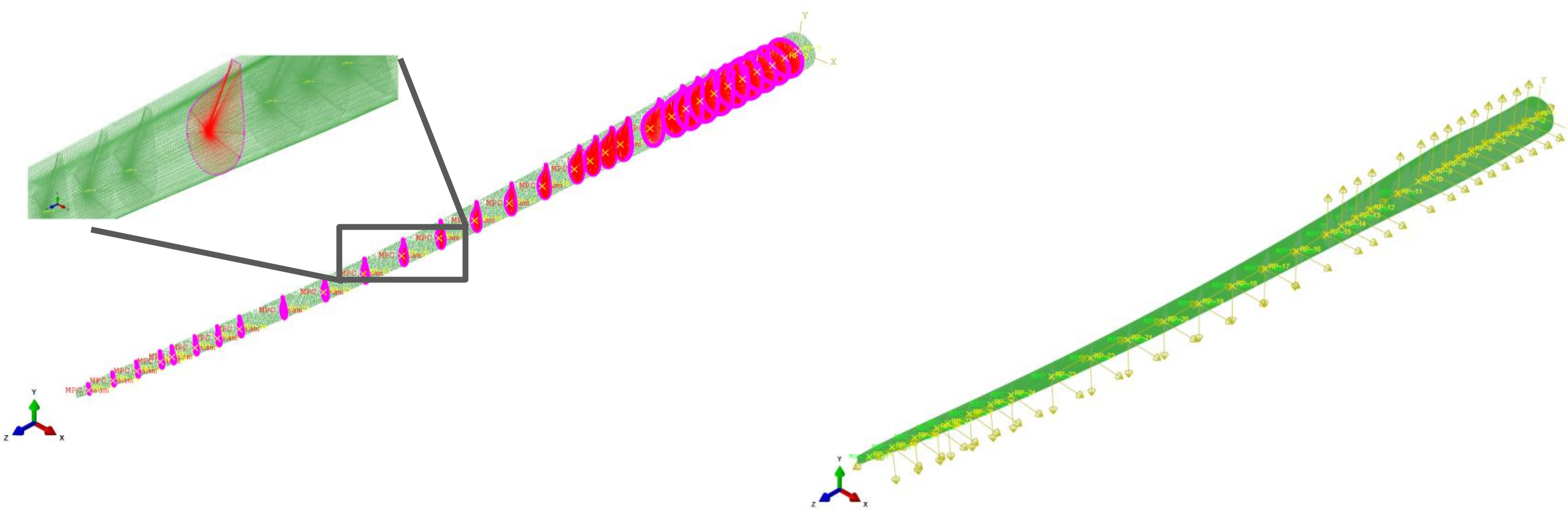
- FE modelling and analysis:
  - Blade level analysis
  - Morphing mechanism
  - Multiscale modelling





Stress analysis (1): Global stability and strength analysis (1)

- A shell FE model is used in the stability and strength analysis
- Aerodynamic loads are distributed along the rotor blade using discrete loads at specific cross sections

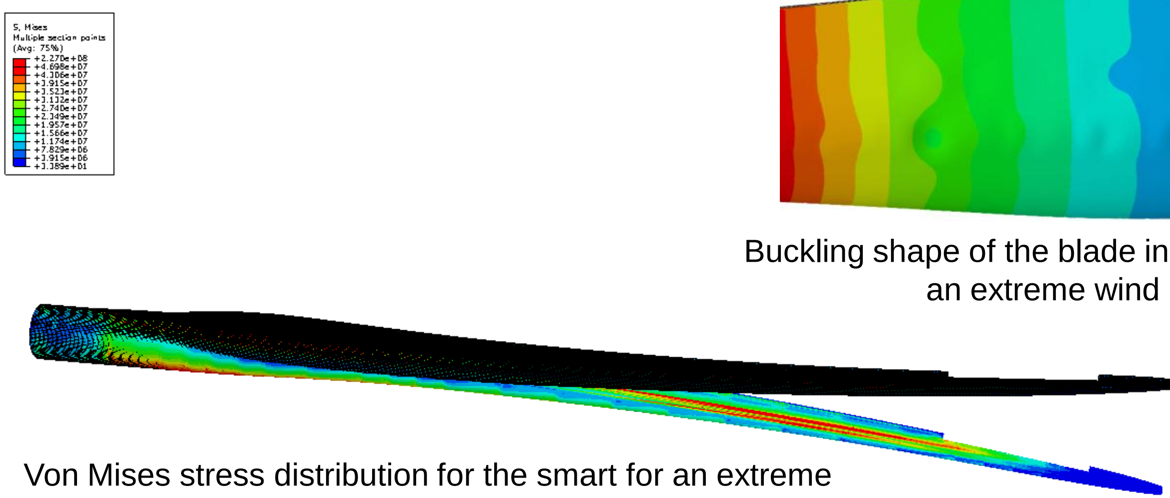


Load distribution along the blade using discrete loads at specific cross sections of the blade.

Stress analysis (1): Global stability and strength analysis (2)

- Geometrically nonlinear finite element analyses were carried out for several extreme load cases
- The results show local buckling in the skin due to the flap-wise loads and in the webs due to the edge-wise loads

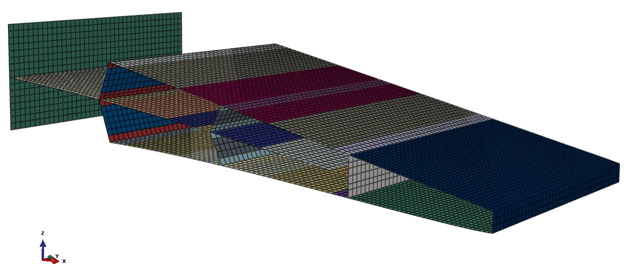
Buckling shape of the blade in the stress analysis for an extreme wind load case



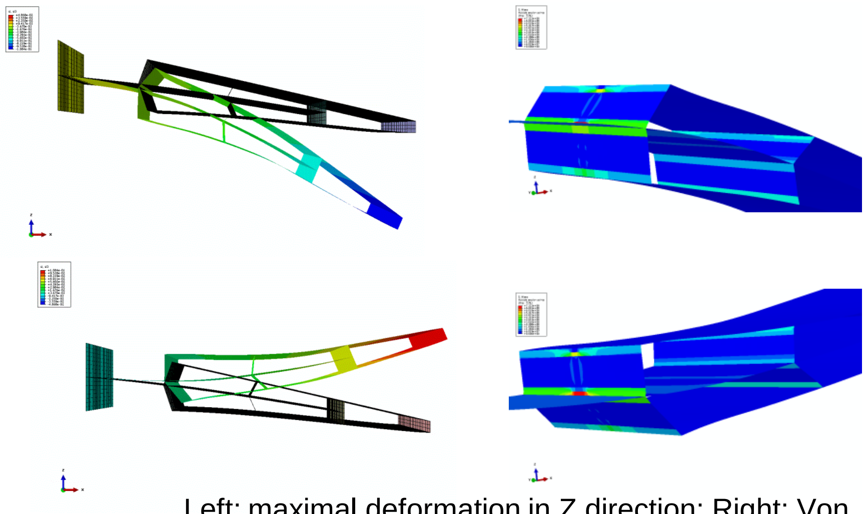
Von Mises stress distribution for the smart for an extreme wind load case

Stress analysis (2): Structural analysis of morphing mechanism (1)

- The stress analysis of the Smart Blades morphing mechanism shows the critical areas of the structure
- Three different variants of the morphing mechanism have been analyzed in order to study the load introduction in the active trailing edge



FE mesh of active trailing edge in ABAQUS

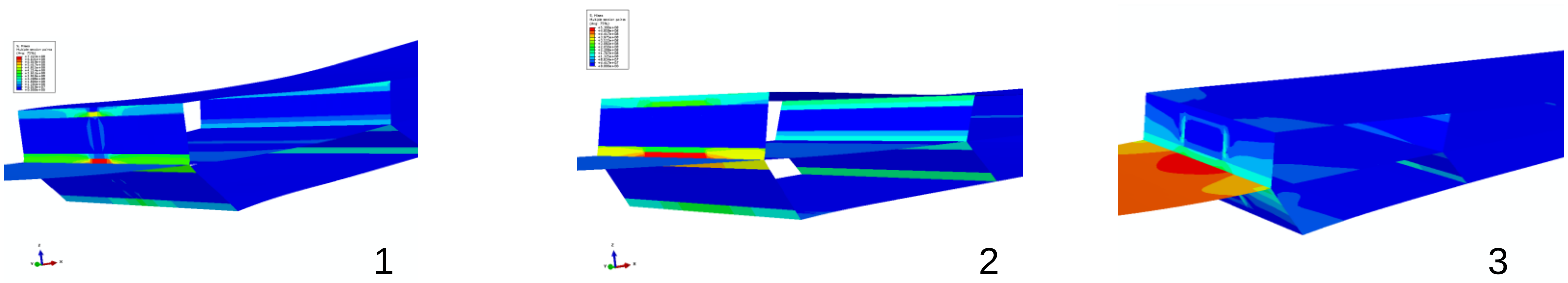


Left: maximal deformation in Z direction; Right: Von Mises stress distribution in the critical areas.

Stress analysis (2): Structural analysis of morphing mechanism (2)

- Variant 2 presents the best structural performance without increasing the mass of the trailing edge

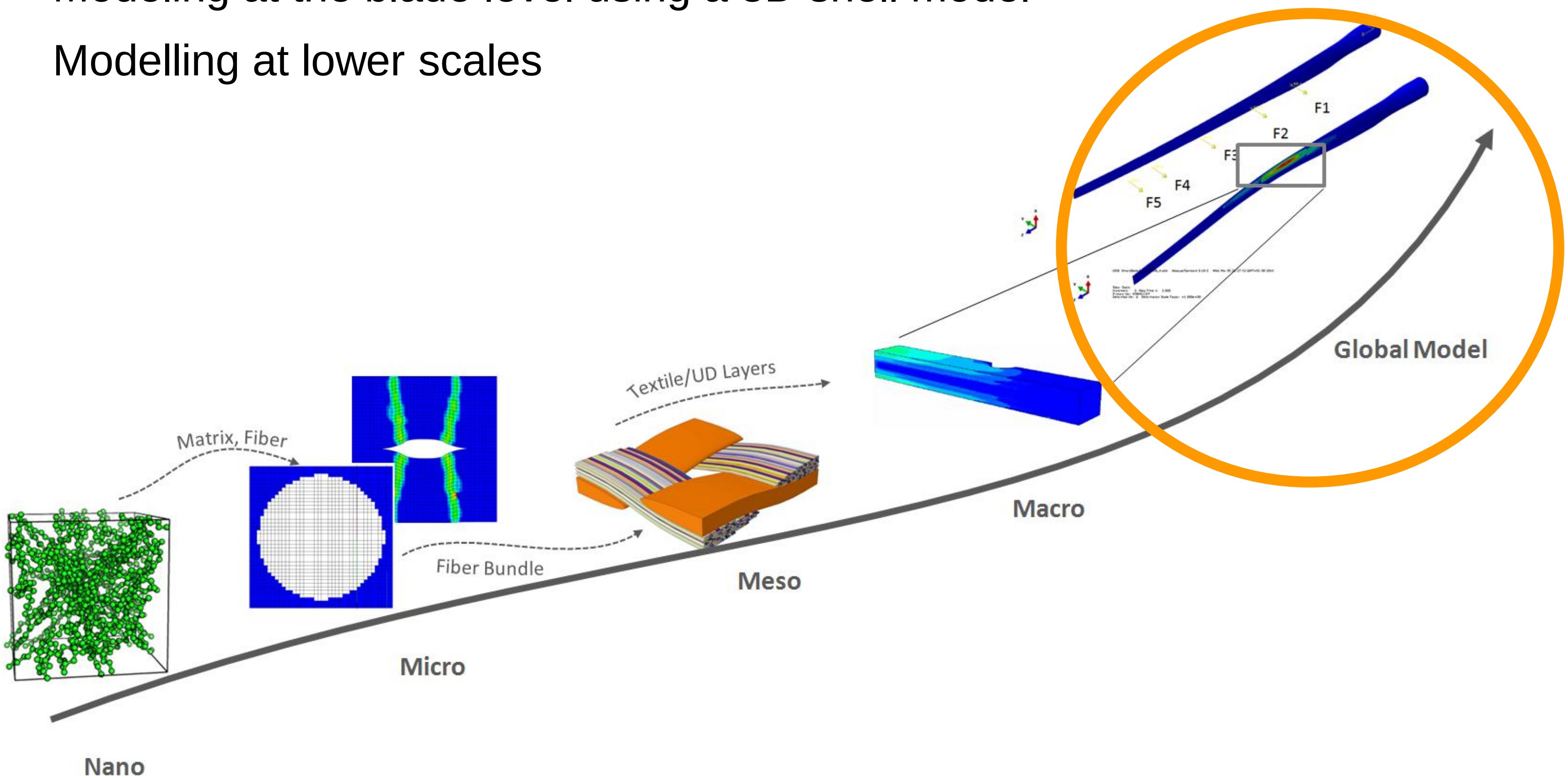
	Variant 1	Variant 2	Variant 3
	95 mm²	568 mm²	568 mm², thicker stringers
Force	400 N	400 N	900 N
Max. ***U***	0,11 [m]	0,11 [m]	0,11 [m]
Max. **σ**	722 [MPa]	530 [MPa]	180.93 [MPa]
Max. **ε**	1.78 %	1.3 %	0.59 %



Critical stress concentration areas of the three different variants to study the load introduction in the active trailing edge (load introduction area and stringer area)

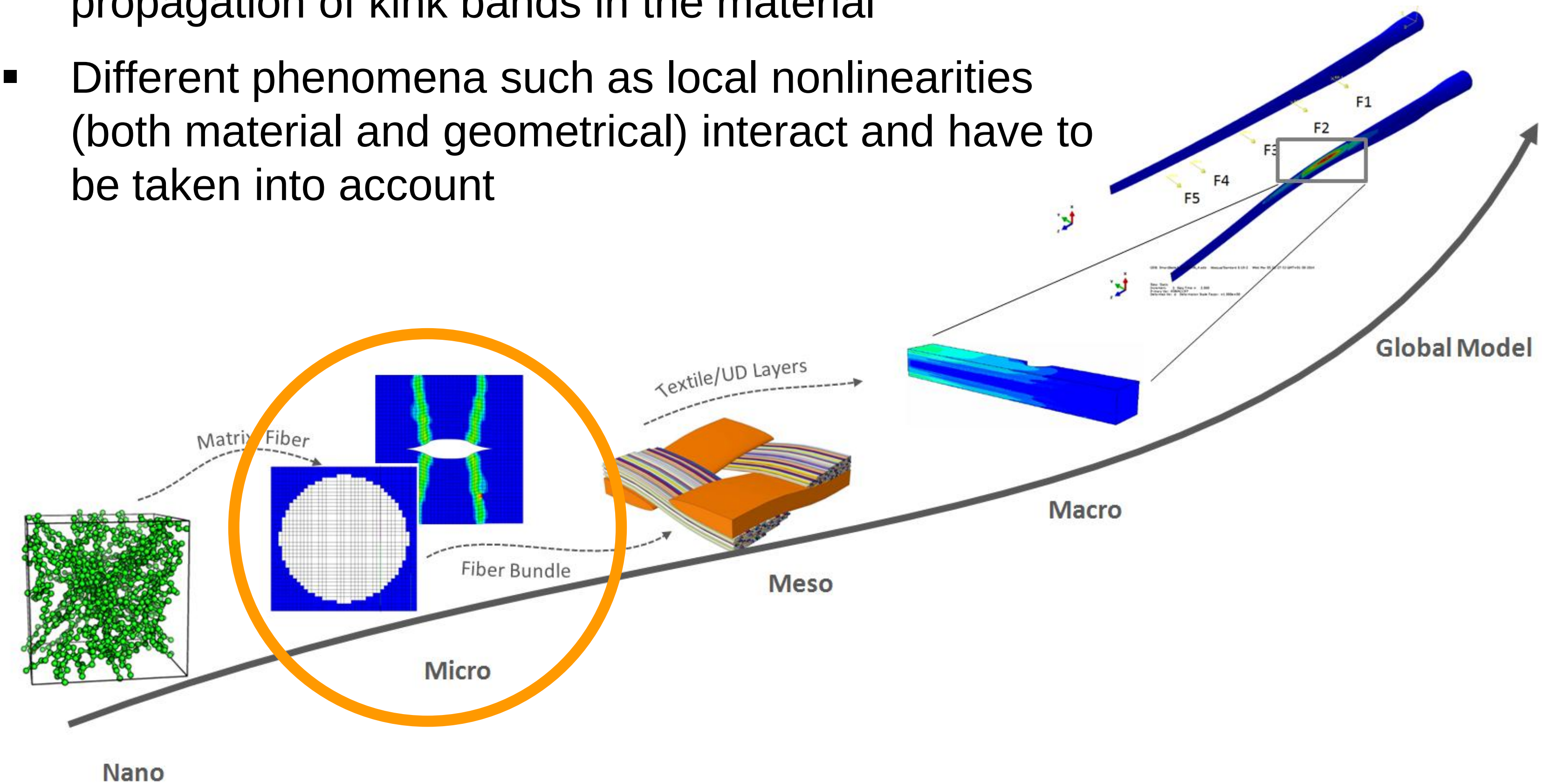
Stress analysis (3):
Towards multiscale modelling

- Modeling at the blade level using a 3D shell model
- Modelling at lower scales



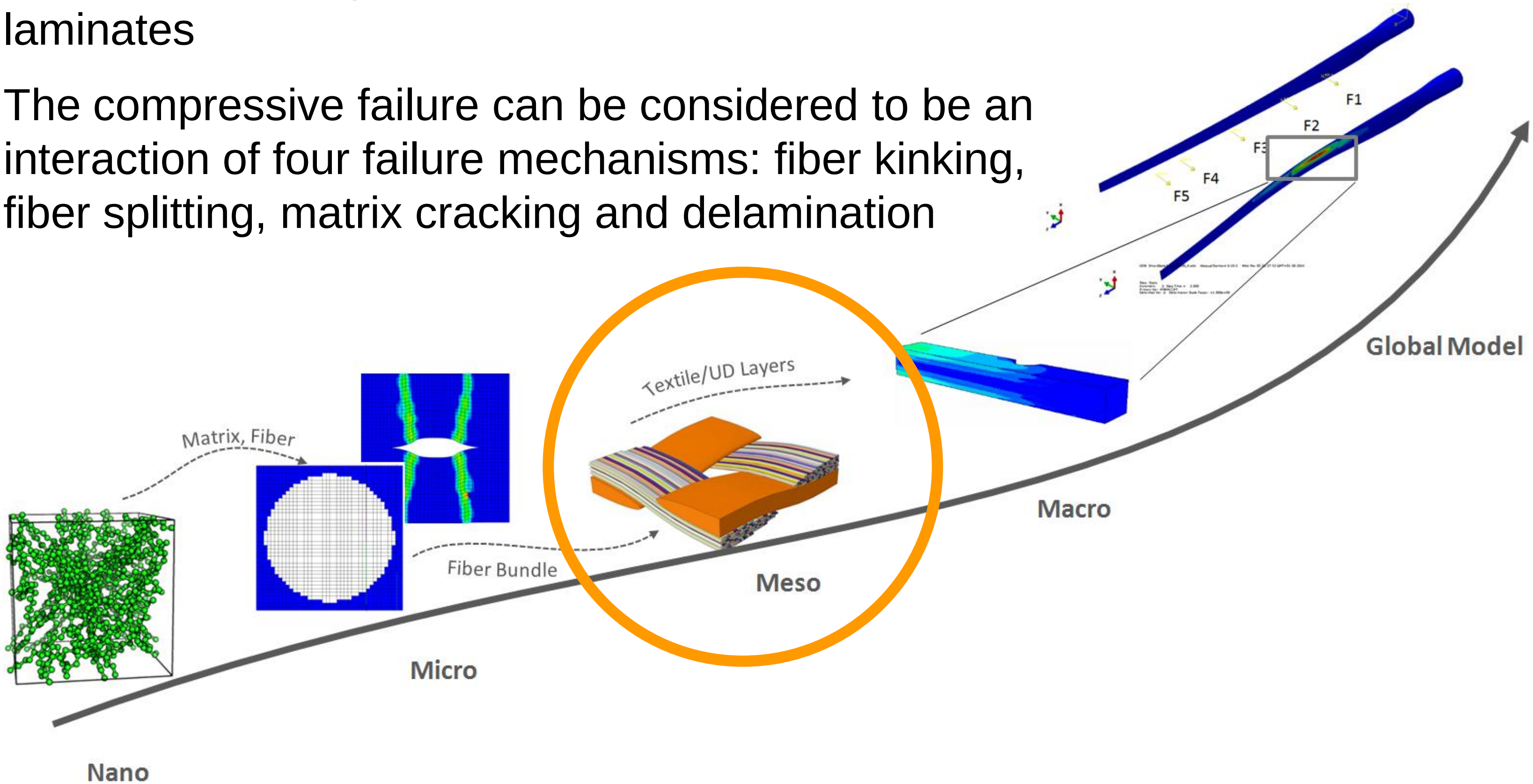
Stress analysis (3): Micro level

- 3D modeling to simulate the initiation and propagation of kink bands in the material
- Different phenomena such as local nonlinearities (both material and geometrical) interact and have to be taken into account



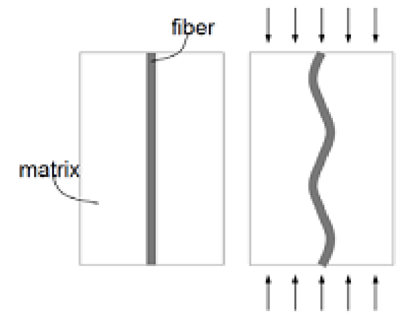
Stress analysis (3): Meso level

- Simulate the compressive failure of multidirectional laminates
- The compressive failure can be considered to be an interaction of four failure mechanisms: fiber kinking, fiber splitting, matrix cracking and delamination



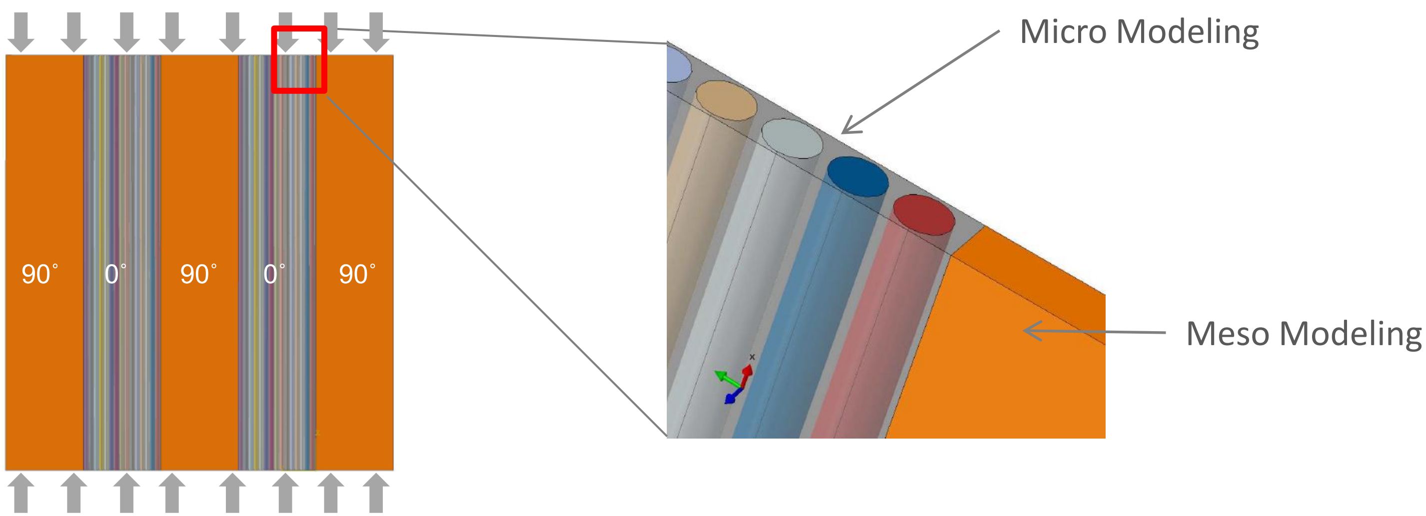
Stress Analysis (3): Hybrid Micro/Meso Model (1)

Fiber misalignments can induce fiber kinking

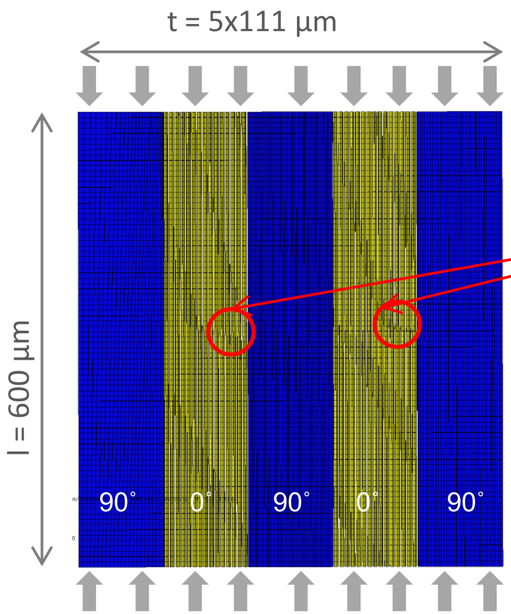


Hybrid Micro-Meso Modeling (Bishara et al., submitted, 2016)

- Micro modeling for the kinking-relevant areas
- Transversely isotropic elasto-plastic material model other areas



Stress Analysis (3): Hybrid Micro/Meso Model (2)



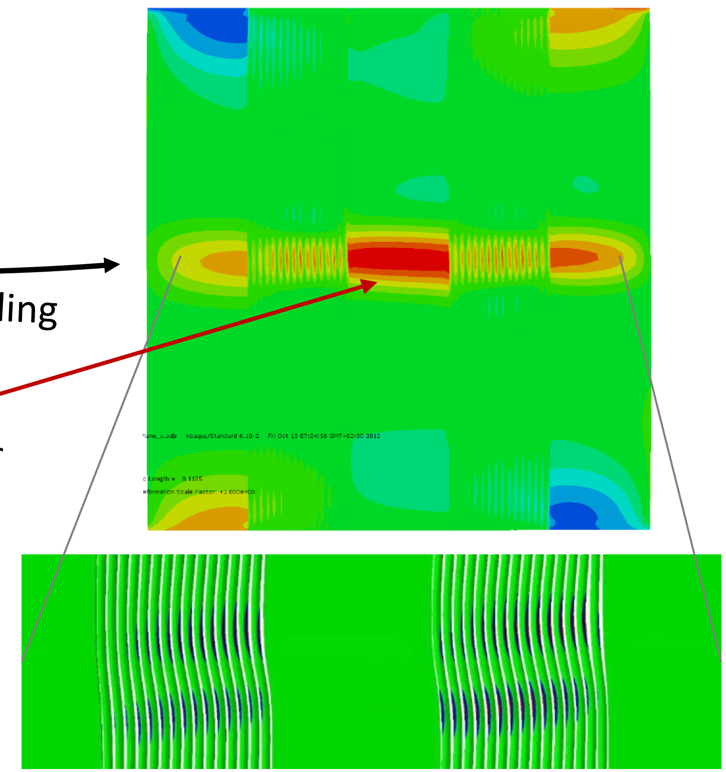
2 local fiber misalignments

Compression Loading

Matrix crack in the 90˚ layer between the kink bands

Results

In-plane shear stress , S_{12}



Goal: Determine knock-down factors and admissible fiber misalignments

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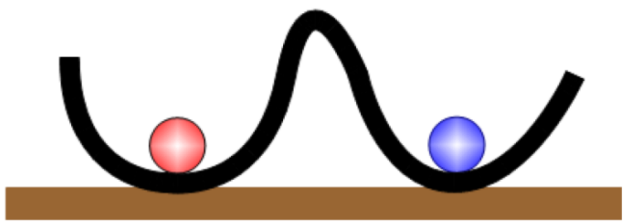
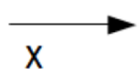
Morphing Blades (1): Introduction multi-stability



Wolfs 2013

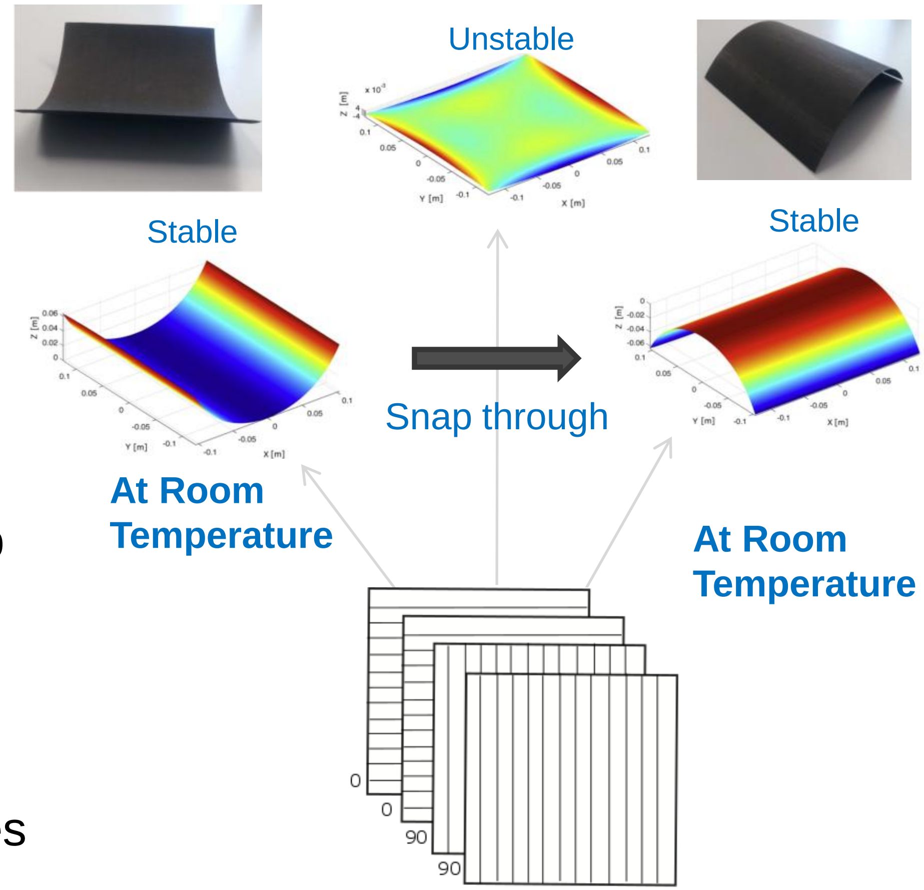


- Several Minima of Potential Energy

- With snap through force one can jump from one stable state to another

- Two ways to achieve:
  - ✓ Isotropic shells can show multistability with initial curvatures
  - ✓ Orthotropic materials yields bistability due to residual stresses (temperature, prestressing)

Multistability in Composites (using Thermal Residual Stresses)



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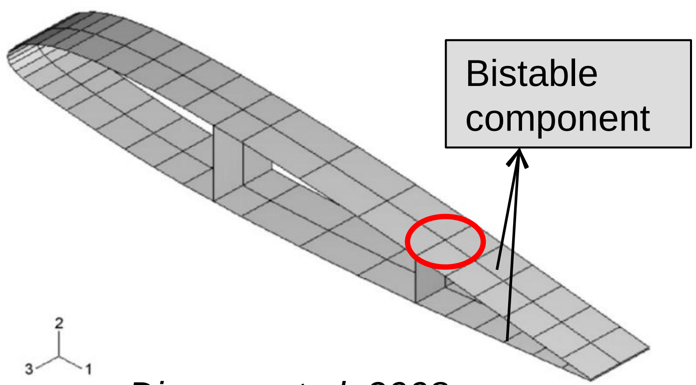
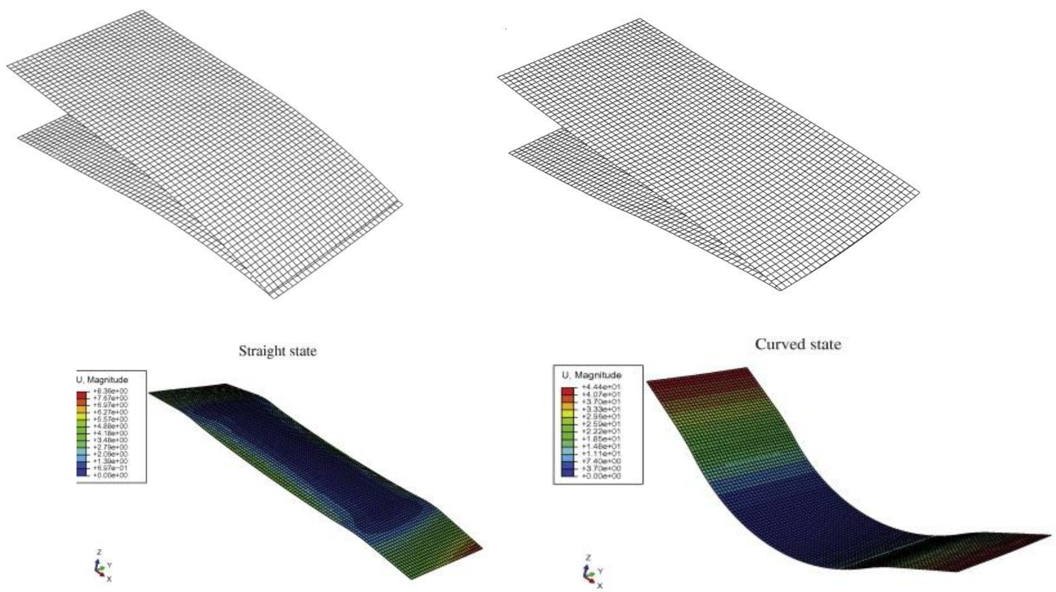
Morphing Blades (2): Multi-stable components in Morphing Rotor Blades

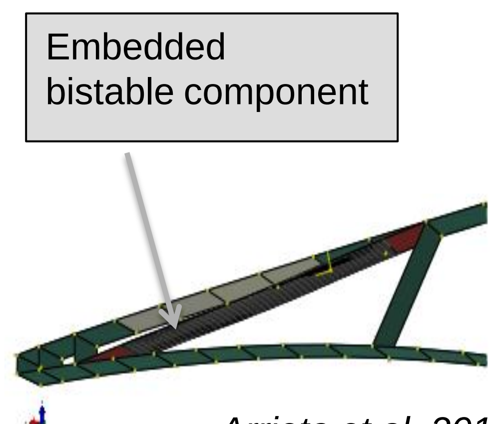
- To reduce fatigue loads in blades due to turbulence, gusts
- Increasing aerodynamic efficiency



Diaconu et al. 2008

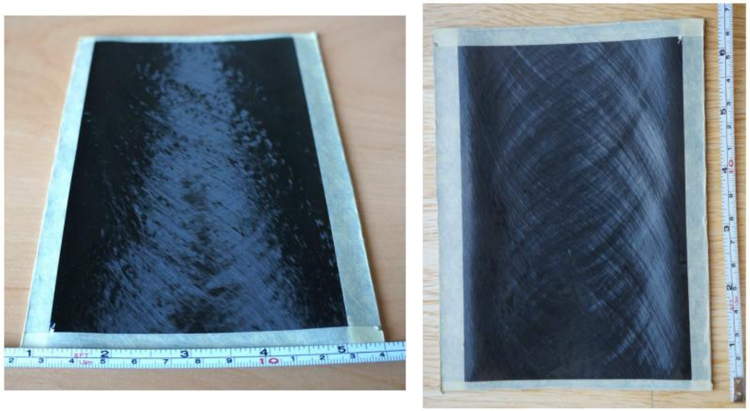
- High snap through forces
- High stress concentration at the interface between load carrying and adaptive structure
- Difficult to integrate
- Single compliant mechanism desired



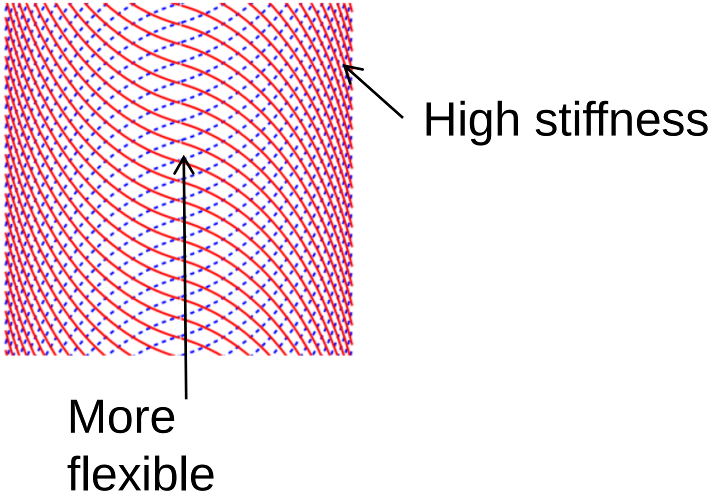


Arrieta et al. 2014

Morphing of VS Laminates (1): Introduction

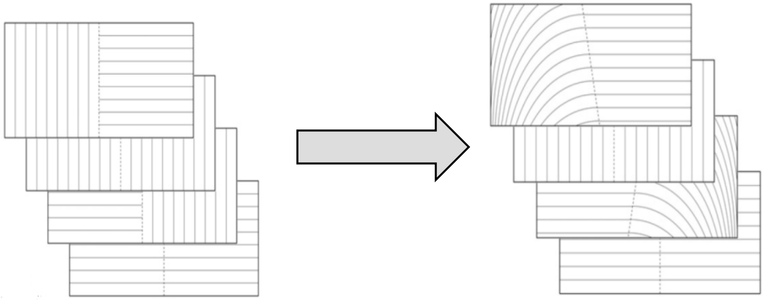


Weaver et al 2009



- Unlike traditional fiber placements, fiber direction is varied spatially
- Increase in freedom of design space
- More efficient composite structures can be created
- Easy integrability
- Lower snap through forces? Some clues from buckling analysis of VSC

Load carrying and flexible at the same time

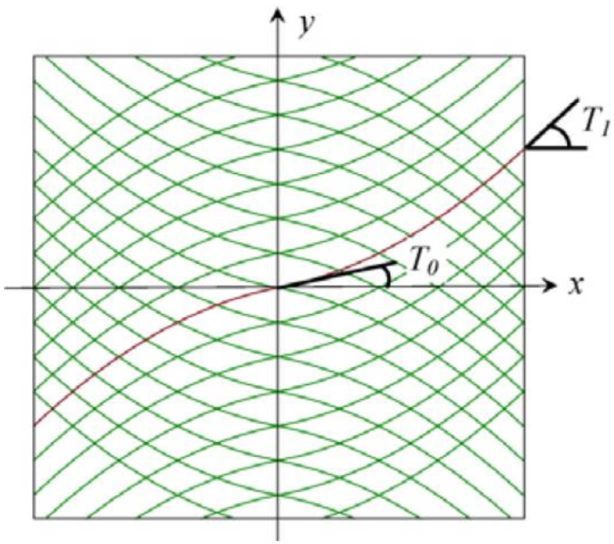


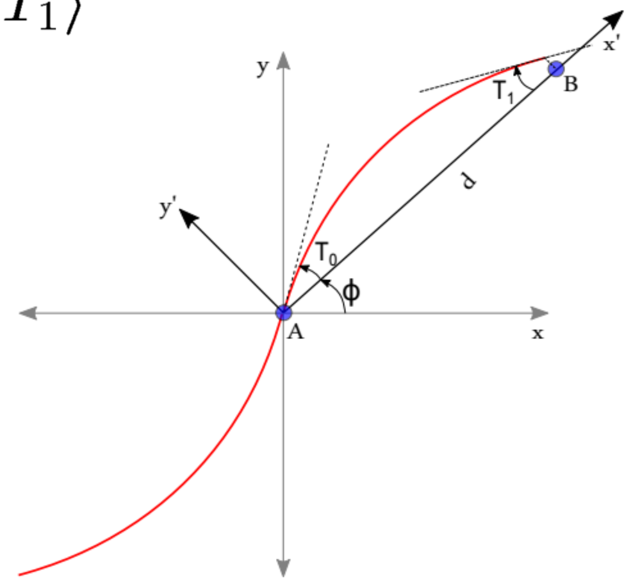
Sousa et al 2013

Morphing of VS Laminates (2): Analysis basics

Angle is varied linearly from center to edges : 3 parameters used to define varying angle-

$$\phi\langle T_0|T_1\rangle$$





$$\theta(x') = \begin{cases} \phi + \frac{(T_0 - T_1)x'}{d} + T_0, & \text{for } -d \le x' \le 0 \\ \phi + \frac{(T_0 - T_1)x'}{d} + T_0, & \text{for } 0 \le x' \le d \end{cases}$$

Fiber orientation angle

$$x' = x\cos\phi + y\sin\phi$$

***ABD matrix** depends upon the coordinates of the plate*
Leading to more complicated equations and higher computational time than straight fibers

Morphing of VS Laminates (3): Semi-analytical and FE Modelling

(Haldar et al.)

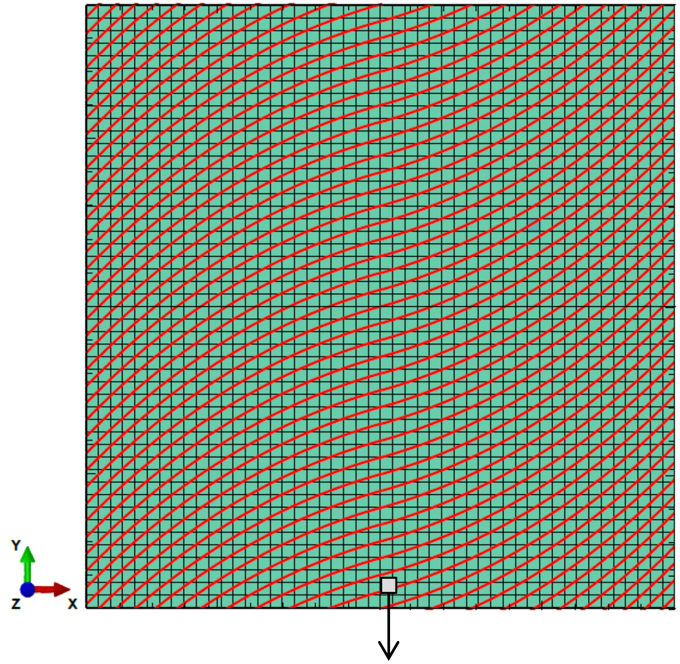
Semi-analytical model:

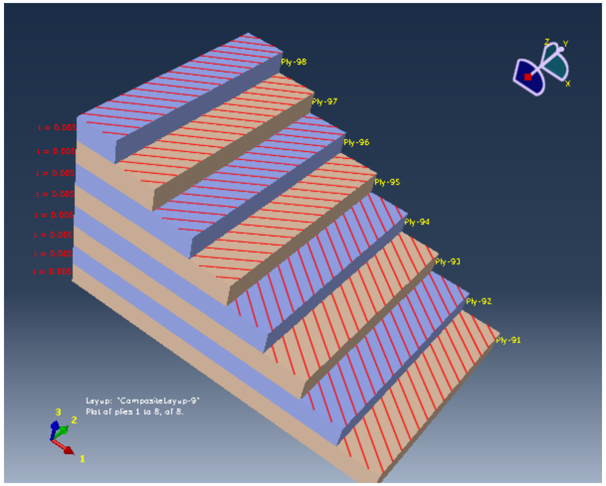
- based on Rayleigh-Ritz approach
- much faster tool than FE
- gives the complete map of all the possible solutions
- both stable and unstable shapes

FE Model:

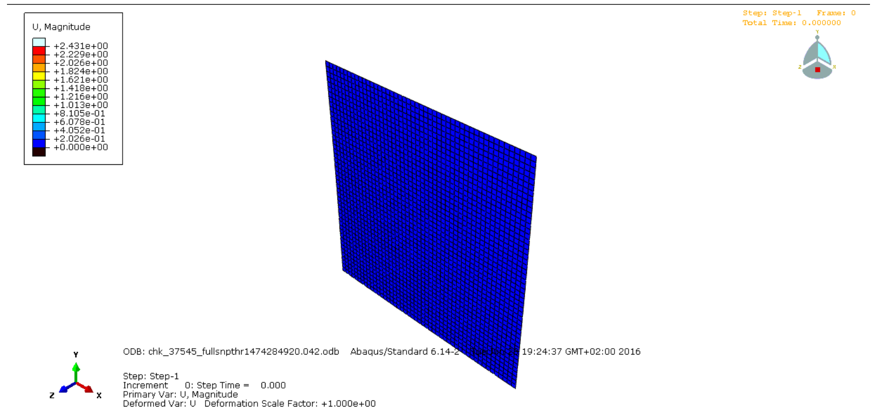
- S4R elements, 2304 elements
- Fixed at center
- Total 8 layers
- $\Delta T = 280^{\circ}$ (cool-down)
- Angle varied discretely in each element

MATLAB routine was written and linked with ABAQUS to assign the fiber orientation for each element discretely in modelling of variable stiffness composites

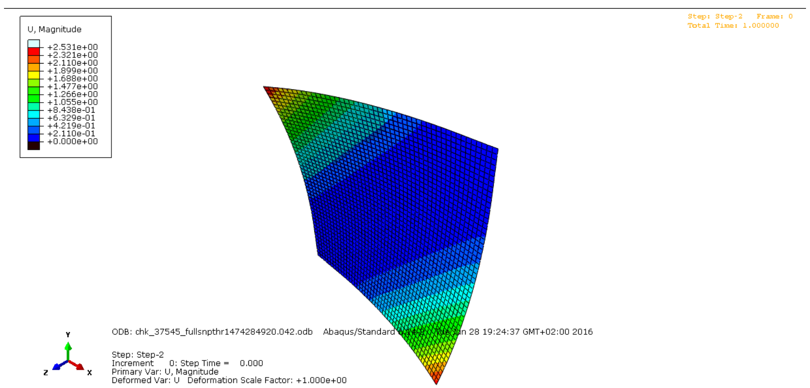


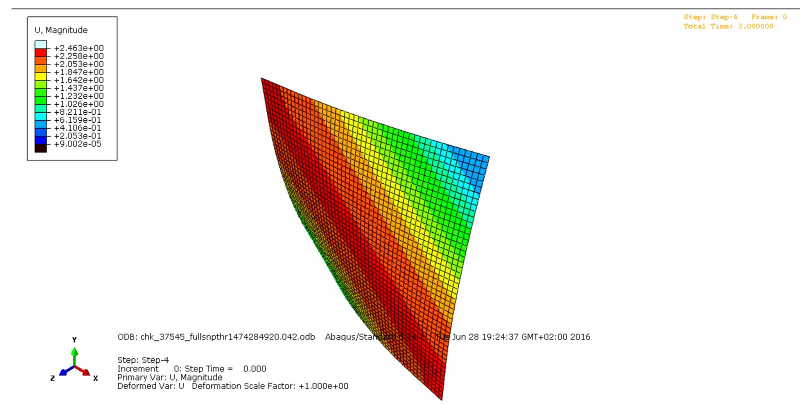


Morphing of VS Laminates (4): FE Modelling



Cool-down
(ΔT = 280° F)

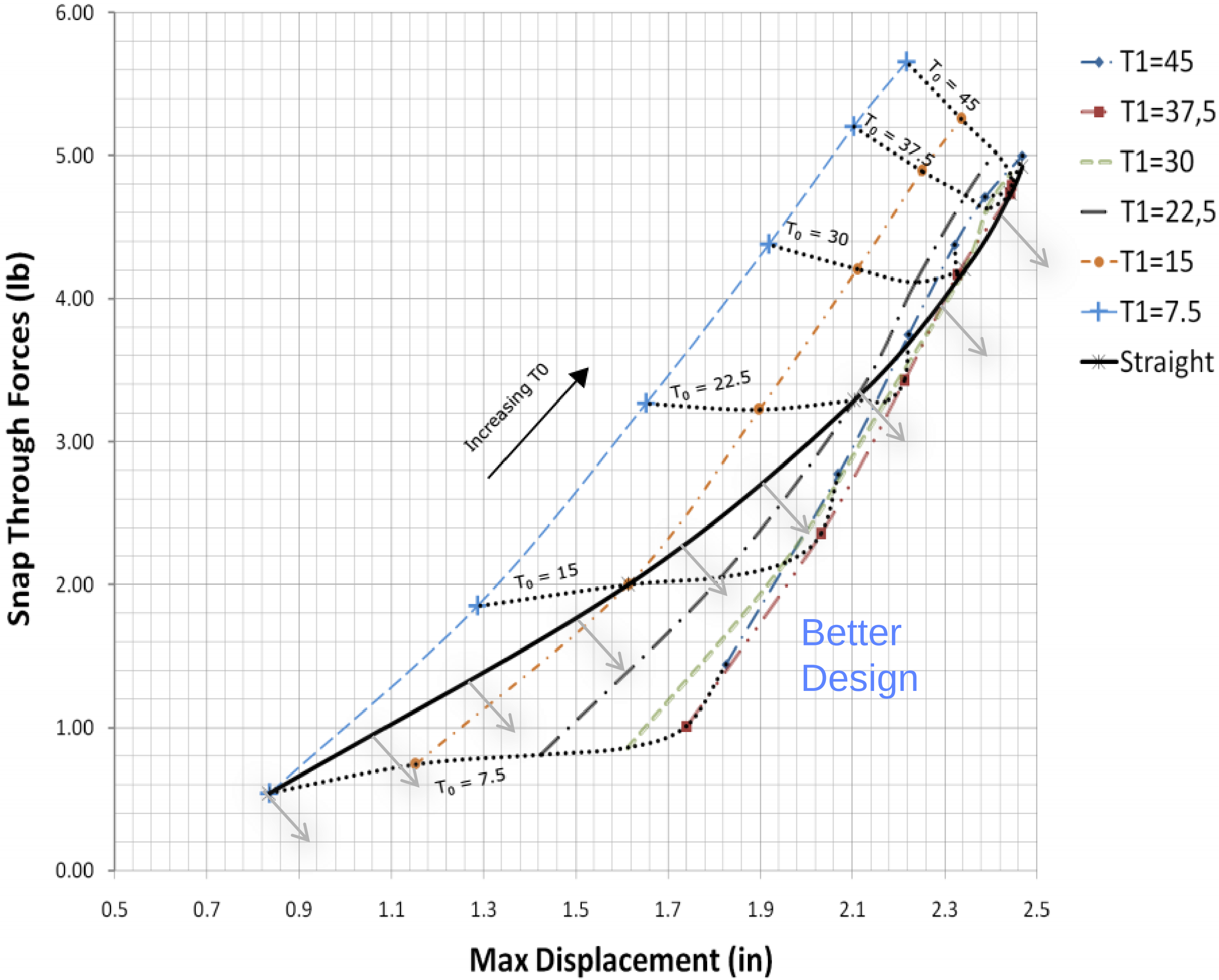




Snapping forward **Snapping backward**

VS Laminate Configuration – [0<37.5/45>$_4$/ 0<-37.5/-45>$_4$]

Morphing of VS Laminates (5):
Snap-Through Forces – Maximum Displacement



- With low snap-through force, one can attain a higher corner displacement
- The points below the straight fiber curve provide a better design
- These designs can be helpful in producing morphing structures which require lower snap through forces.

Concluding Remarks

– Structural analysis tools for evaluating the effectiveness of rotor blades with a morphing trailing edge and alternative concepts,

- Dynamic analysis tools
- Fatigue analysis and stress analysis tools
- Morphing trailing edge concepts

have been presented.

– Interdisciplinary integration of these tools and concepts,

- Aero-servo-elastic coupling using detailed structural models
- Fatigue damage analysis and multi-scale progressive failure analysis
- Using multi-stable components in a morphing trailing edge

in the analysis and design process remains our challenge.

Structural Analysis Tools for Rotor Blades with Morphing Trailing Edge

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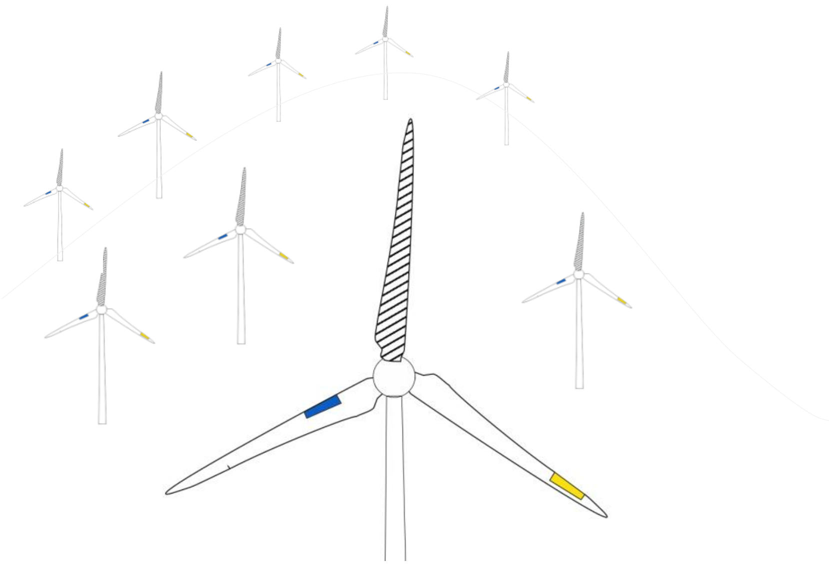

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