Tidal Research at WMC

October 24, 2016, WMC

Remco Brood

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Knowledge Centre WMC
Wind turbine Materials and Constructions

Contents

- Full scale blade testing
- Experimental/numerical characterization of hygrothermal ageing in composite laminates
- Simulation of loads on ocean current turbines with the FOCUS6 software package

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Full scale blade testing at WMC

September 29, 2016, WMC

Ramon Obdam

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Knowledge Centre WMC
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Overview

- Purpose of full scale blade testing
- Determining mass and COG
- Natural frequency and modal analysis
- Static tests
- Fatigue test(s)
- Post-fatigue static tests
- Blade test simulation and analysis in FOCUS6

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Purpose of full scale blade testing

To demonstrate that the design and production of a blade type is sound:

- DNVGL-ST-0164, IEC61400-23
- Show that the blade can withstand both the design *ultimate* and the *fatigue* loads
- Prove the validity of the design models:
  - Mass and COG
  - Natural frequencies
  - Static deflections (stiffness distribution)

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Full scale blade test program

Proposed minimum test programme according to *IEC 61400-23*:

- Determining mass and COG
- Natural frequency and modal analysis
- Static tests
- Fatigue test(s)
- Post fatigue static tests

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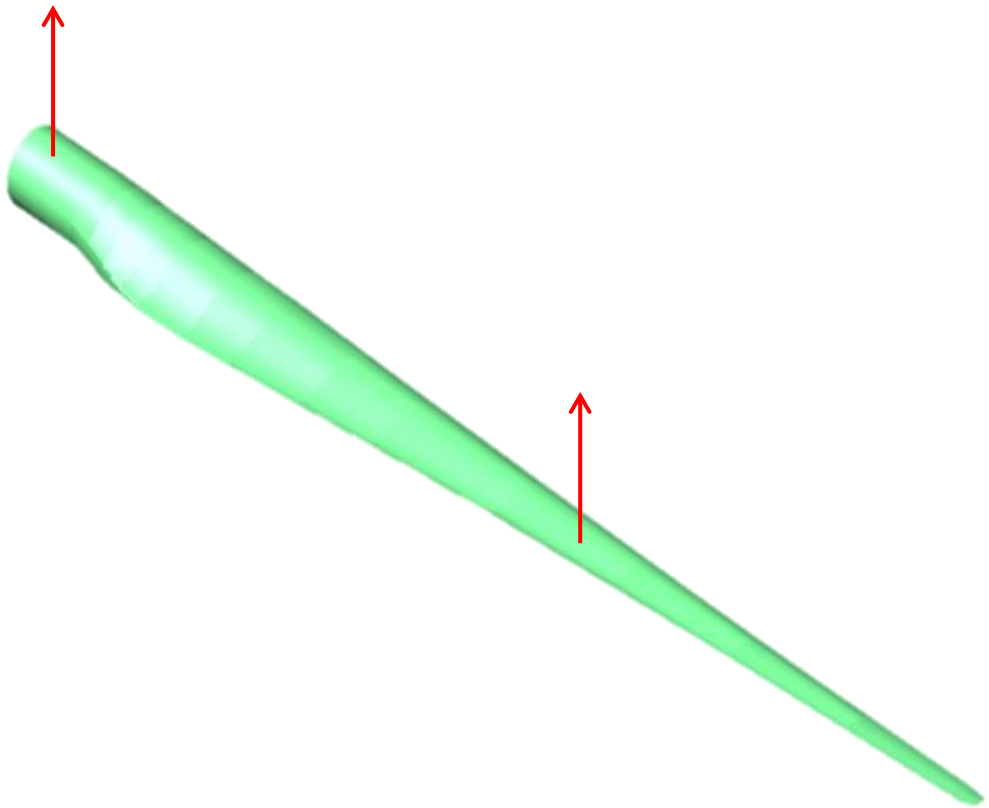
Determining blade mass and COG

Blade is hoisted at two points

Lifting loads are measured by two loadcells



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Natural frequency and modal analysis

Determine:

- Blade natural frequencies
- Mode shapes
- At least first two flap and edge frequencies

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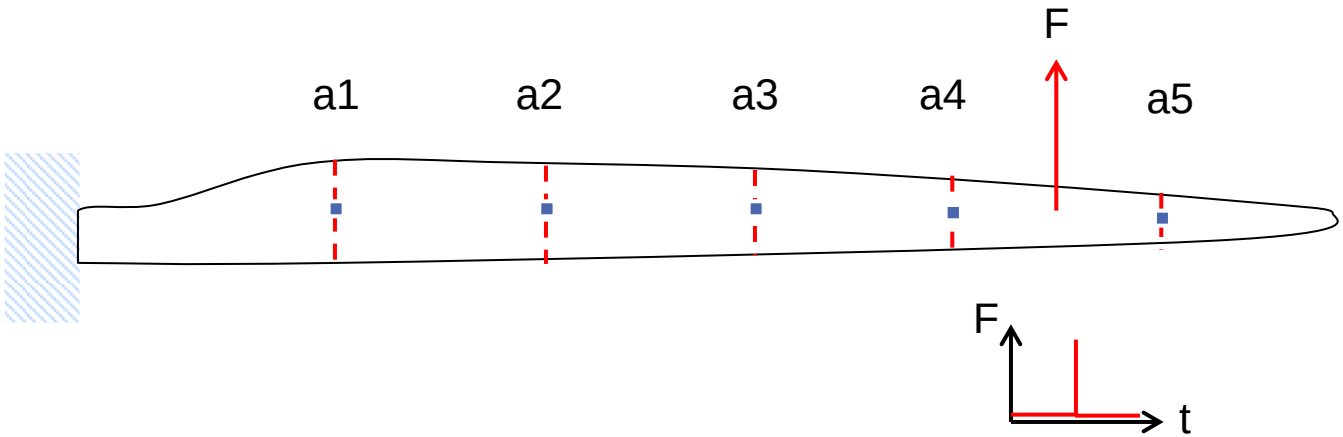
Natural frequency and modal analysis

Setup:

- Blade is fixed at the root
- Accelerometers are placed at multiple cross-sections
- Blade is given an impact at one location



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Natural frequency and modal analysis

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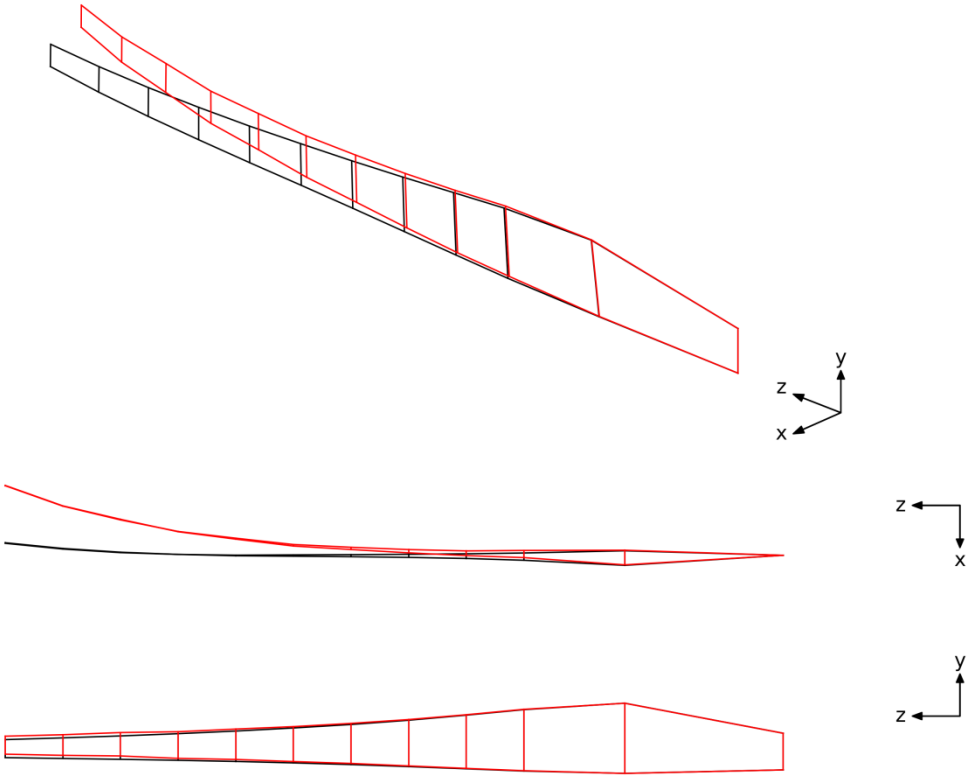
Natural frequency and modal analysis

Example of resulting mode shape:



Measuring accelerations in three directions results in mode shapes with combined flap, edge and torsion

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Static tests

Goals static test:

- Show blade can withstand ultimate design loads (i.e. ultimate limit state is not reached)
- Compare model strains and deflections to measurement

Design ultimate moment curve is derived from turbine load set (FOCUS, BLADED)

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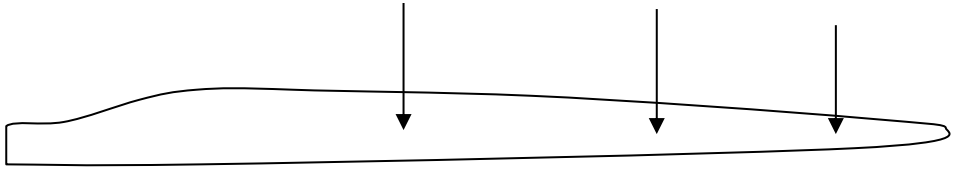
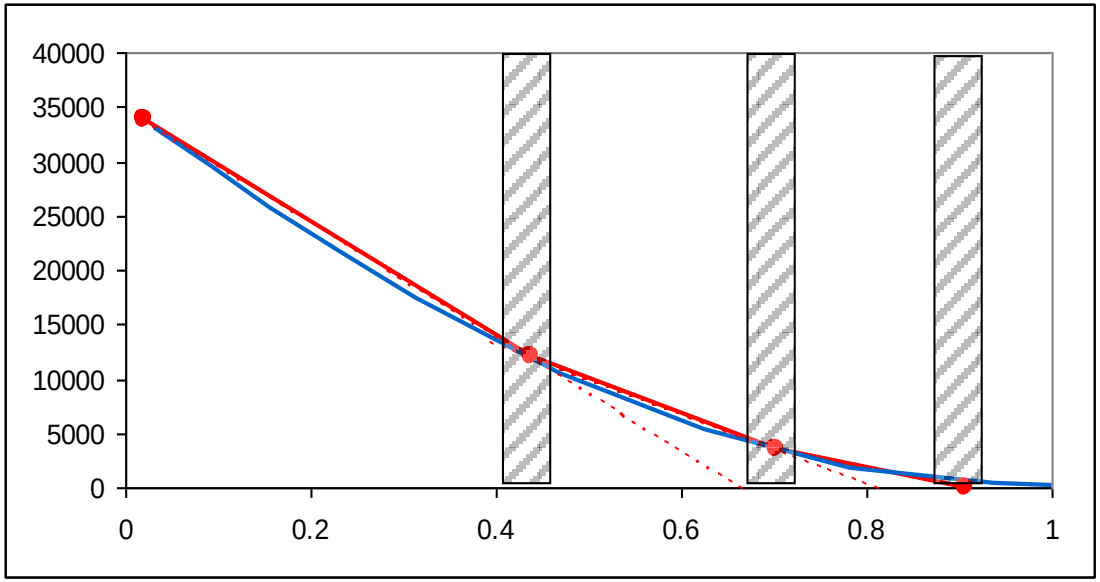
Static tests

Static moment distribution is approximated by multiple point loads





Not properly tested

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Static tests

Test setup:

- Blade is fixed at the root (via blade bearing)
- Blade bolts are instrumented to measure loads in bolts during test
- Strain gauges are placed at various locations along the blade (typically 100+ channels)
- Wire transducers are used to measure blade deflections (in 3D)

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Static tests

Static loads are applied using load introduction saddles:

- Shaped to local blade profile
- Can not be placed at critical cross-sections
- Loads should only be applied perpendicular to the deformed blade axis
- Loadcells are used to measure applied loads

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Fatigue test

Fatigue damage due to 20 years design life compressed to a test of approximately 1-2 months:

- Increasing the frequency
- Omitting non-damaging cycles
- Increasing the load

Regular inspections to check and mark blade damage

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Single-axial fatigue test (resonance)

- **Advantages**
  - Simple hardware
  - Simple tuning of bending moment distribution
  - High frequency
  - Low energy consumption
  - Distributed loading
- **Disadvantages**
  - Separate flap and edge test
  - Limited by blade mode shape
  - Not testing total circumference

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Bi-axial fatigue test (near resonance)

- **Advantages**
  - Accurate coordination of flat & edge loading combinations
  - Torsion loading
  - Short test time
  - All R-values, weight compensation possible
  - Moderate energy consumption
- **Disadvantages**
  - More complicated hardware and controlling
  - Tuning of moment curve requires additional hardware

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Post fatigue static tests

- Same as previous static tests
- Show blade strength and stiffness is not severely reduced by fatigue damage
- Optionally a test to failure to determine the ultimate limit state

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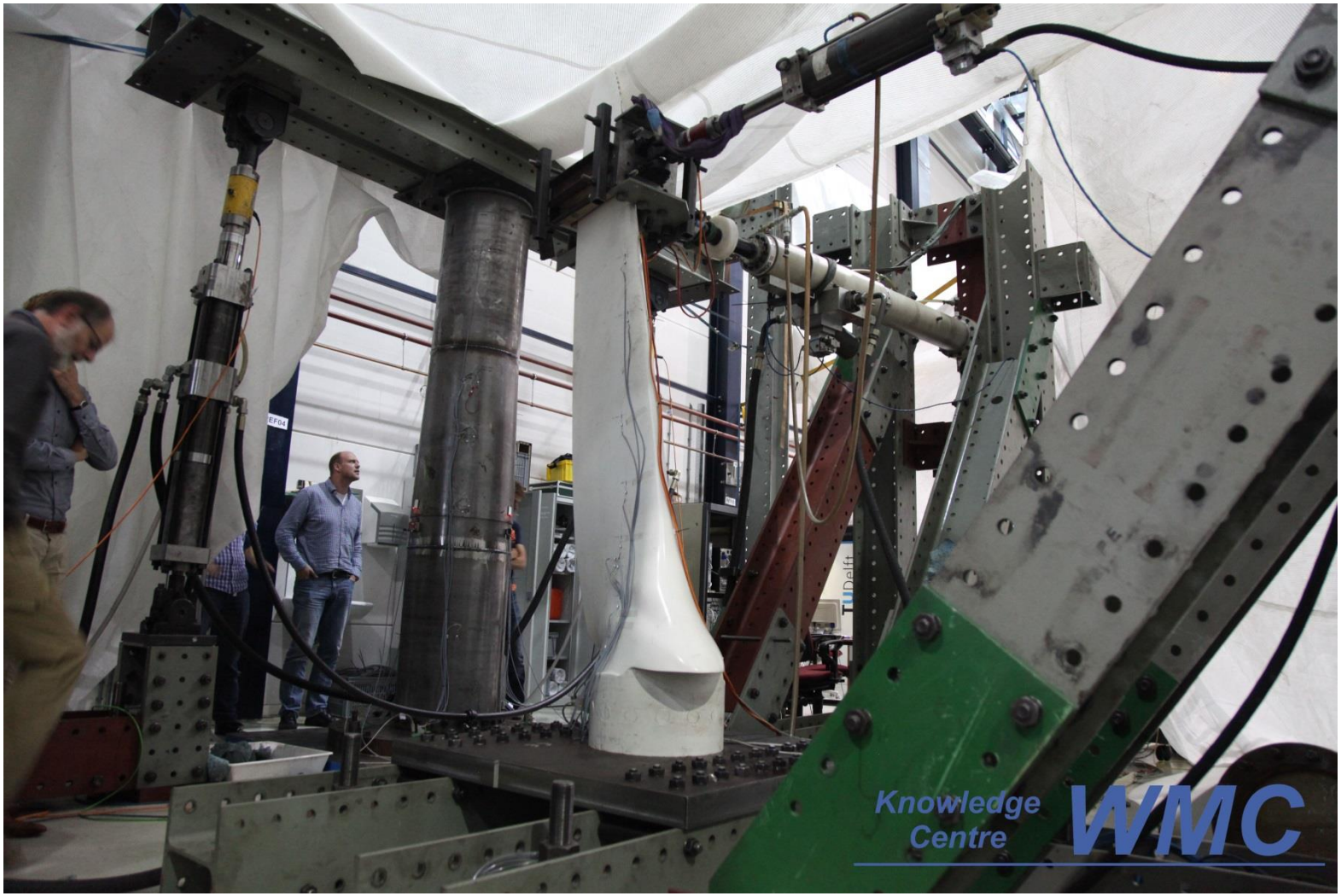
Bi-axial Fatigue test on tidal blade



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Experimental/Numerical Characterisation of Hygrothermal Ageing in Laminate Composites

October 24, 2016, Delft

Iuri Rocha

R.P.L. Nijssen

F.P. van der Meer

L.J. Sluys

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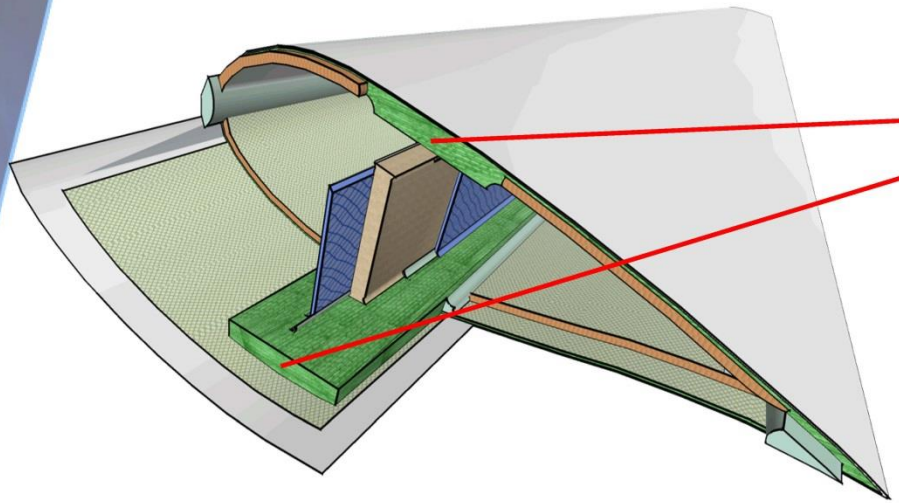
Environmental Loads on Blades

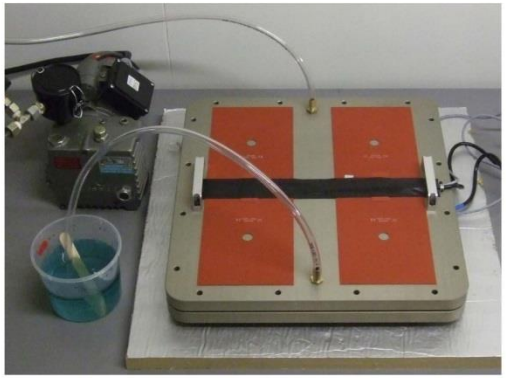


50°C
4800 h

- High/low temperatures
- Moisture ingression
- UV radiation
- Erosion
- Biologic attack

Experimental Investigation

- Manufacturing

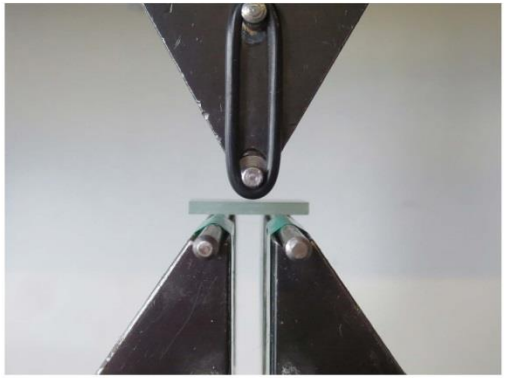


- RIMR135/RIMH1366 epoxy system
- Unidirectional E-Glass fabric
- Vacuum infusion molding
- Short beams for interlaminar shear

- Conditioning

- Demineralised water at 50°C
- Moisture-free reference specimens
- Ageing durations from 250h to 2000h
- Sets tested wet and after being redried

- Mech. testing

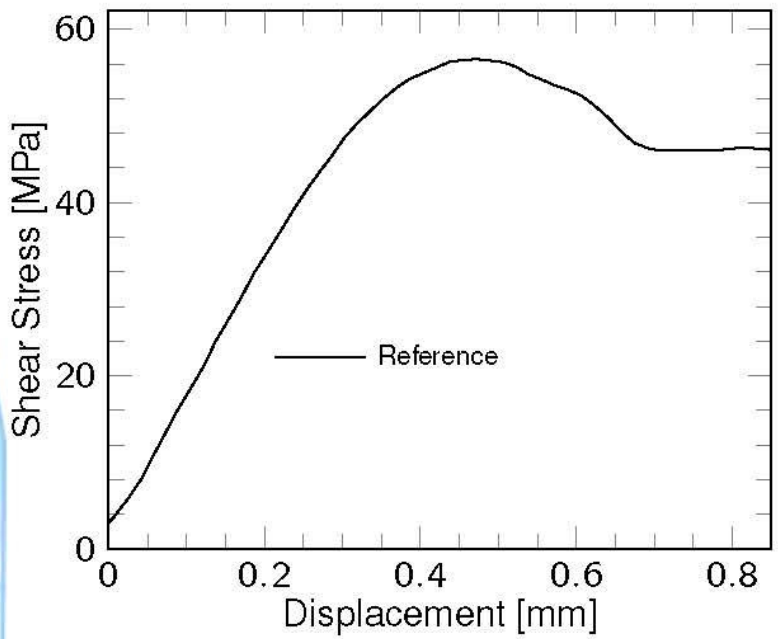


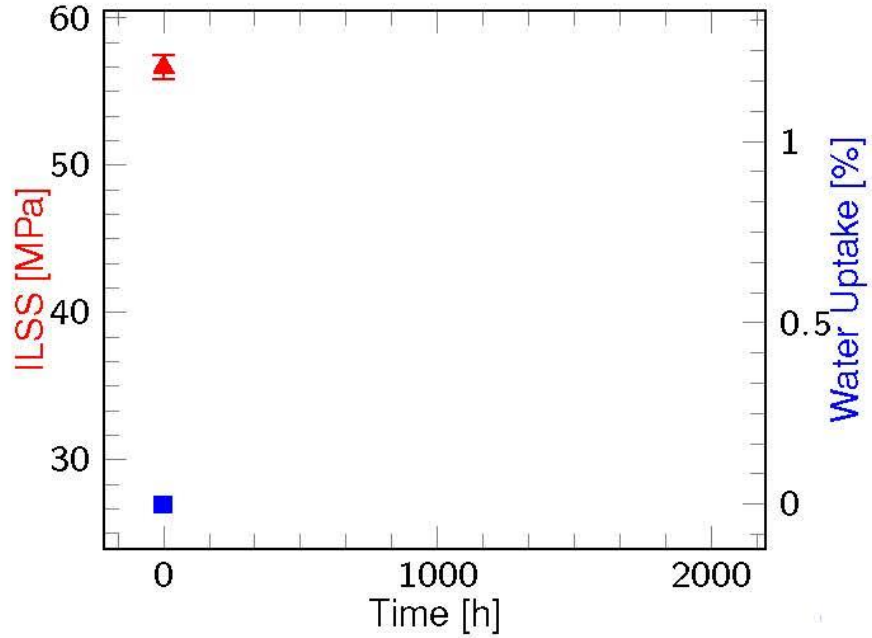
- 3-point bending at 1 mm/min speed
- Sets of 10 tests for each condition
- Interlaminar shear stress calculated as:

$$\tau = \frac{3}{4} \cdot \frac{F}{b \cdot h}$$

Experimental Investigation

- **Results from mechanical tests:**
  - Up to 50% strength decrease after immersion
  - Strength decreases linearly with water uptake
  - Permanent material degradation was observed





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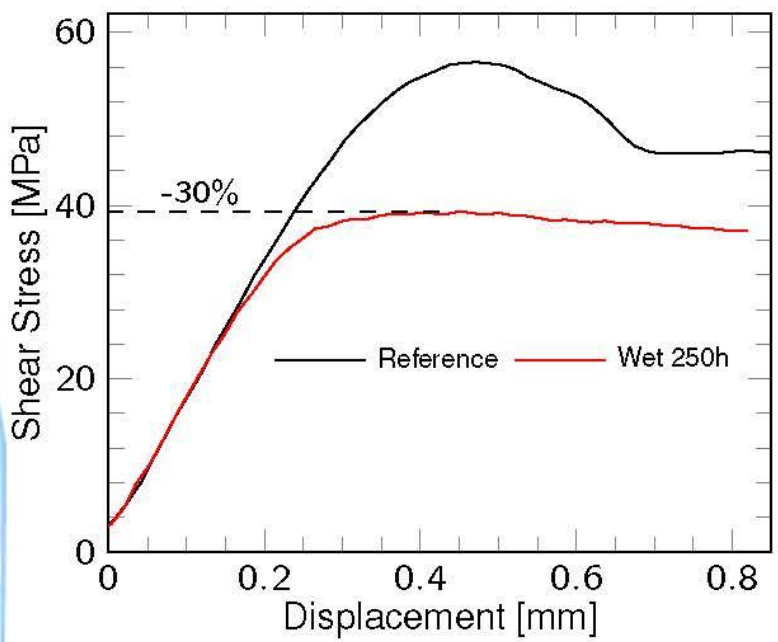

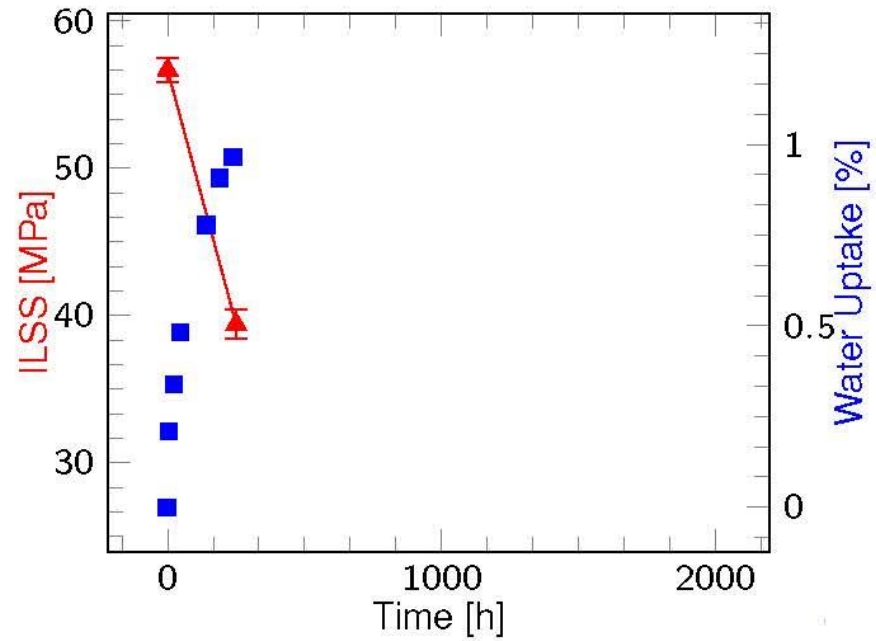

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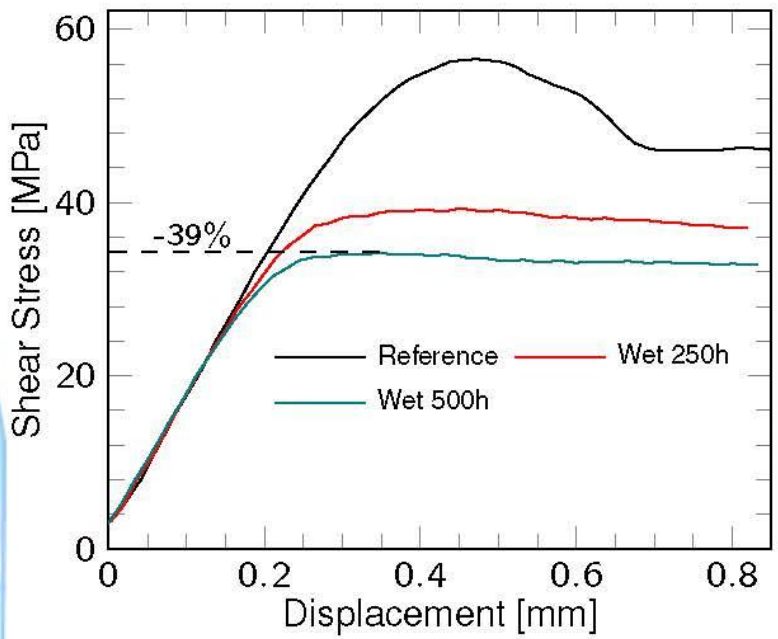

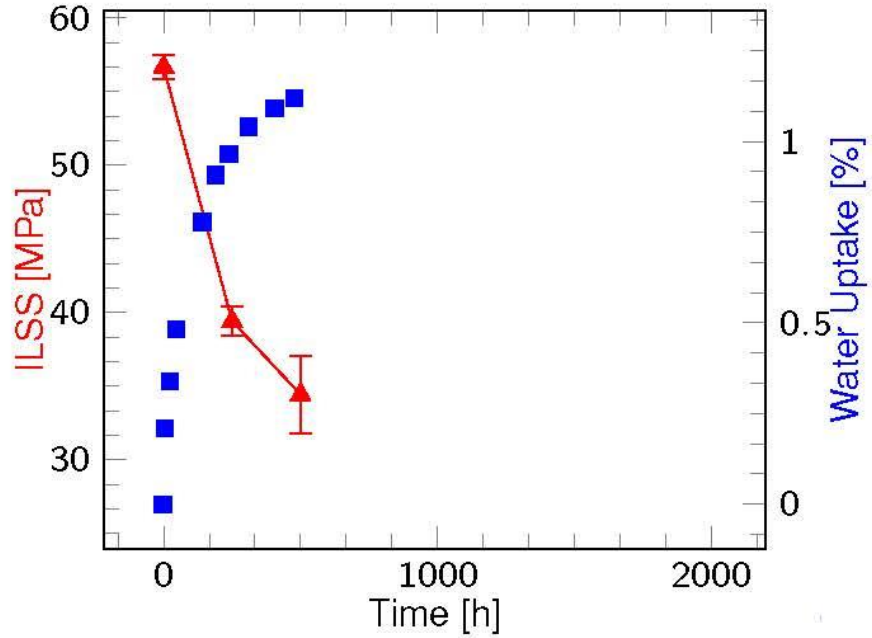

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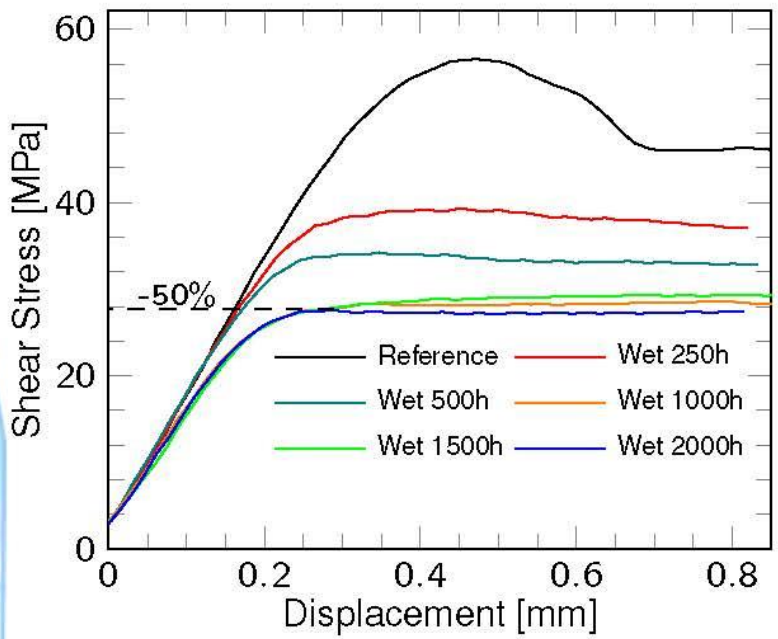

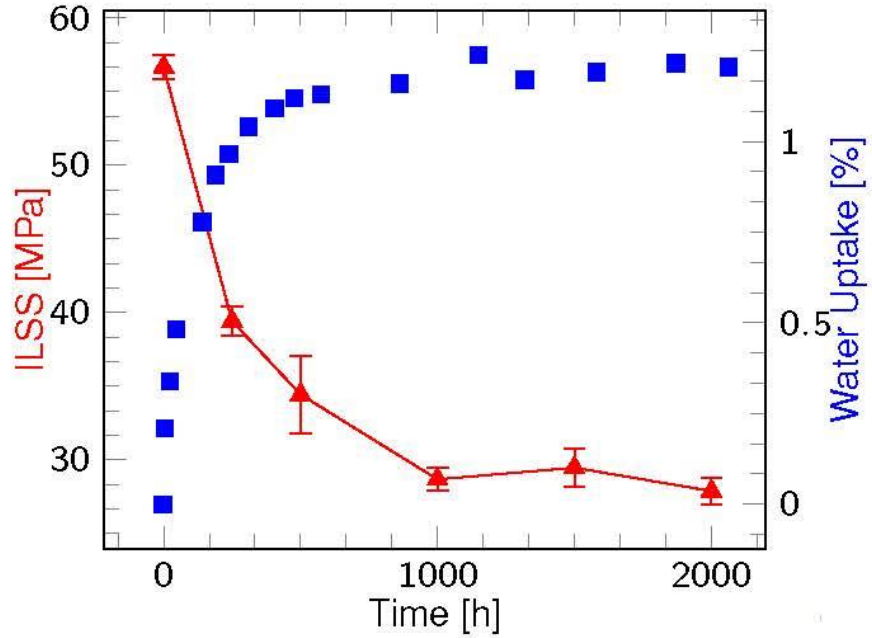

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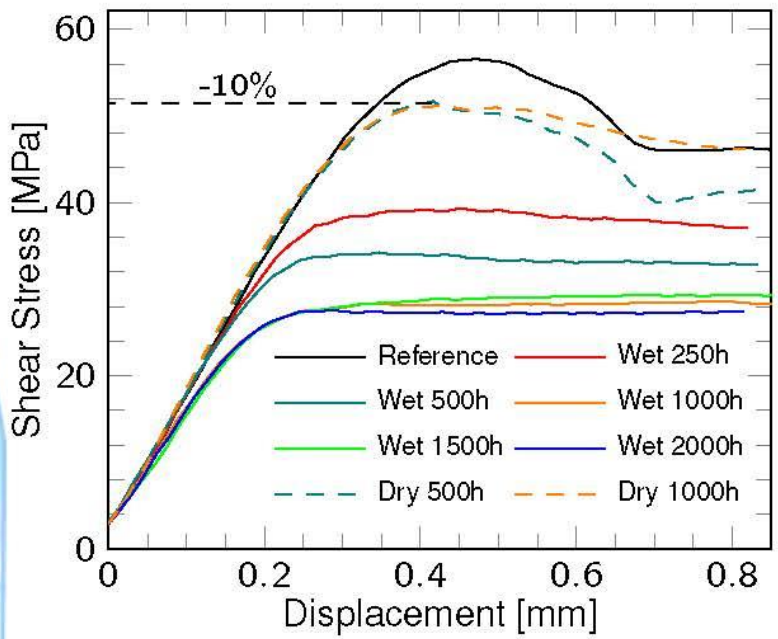
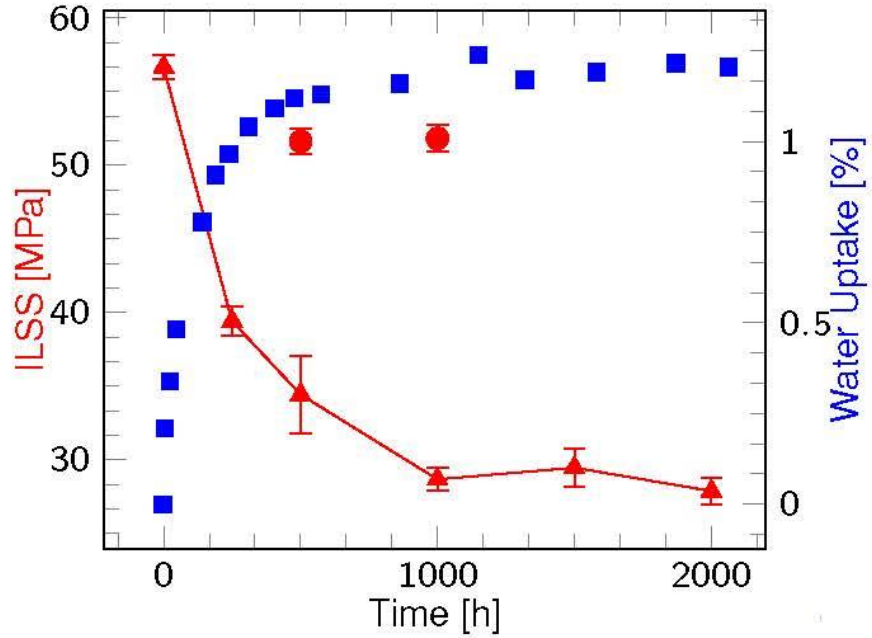
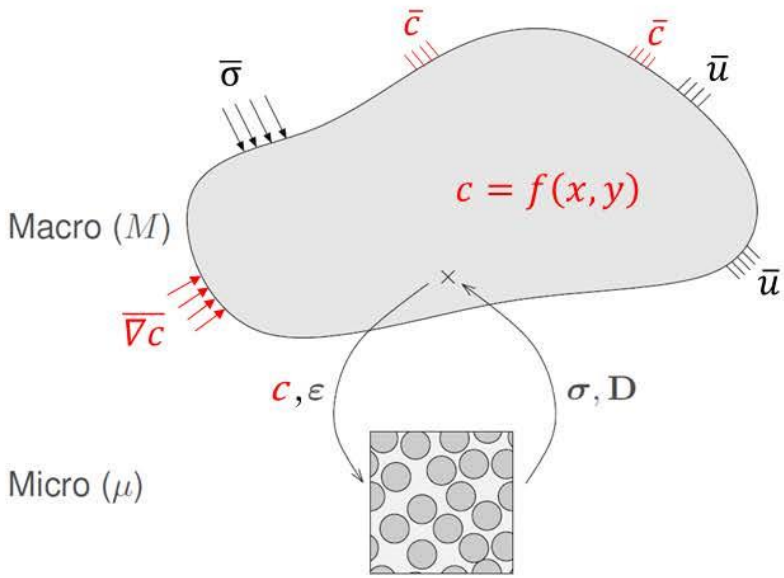




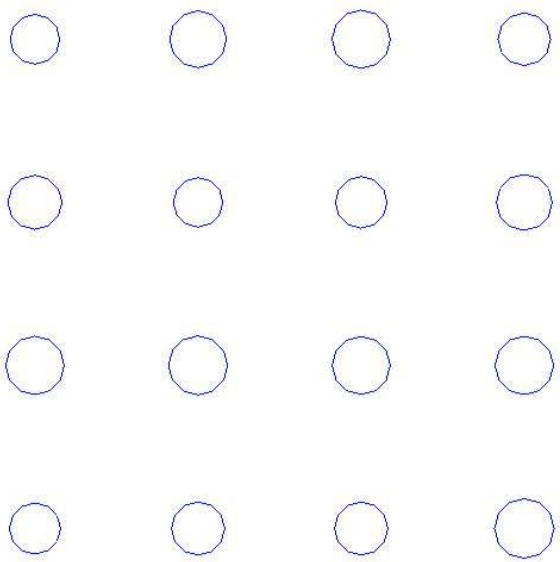
Multiscale Analysis

- **Concurrent (FE^2) homogenization:**
  - Micro-BC's obtained from macro-scale strain
  - Macroscopic local response obtained from RVE
  - Embedded FE model at each integration point
  - Multiphysics $\rightarrow$ Modification of classic FE^2:
    - Macro diffusion $\rightarrow$ micro swelling $\rightarrow$ macro stresses



Micromechanical Model

- **Representative Volume Element (RVE):**
  - 2D with fibres oriented out-of-plane
  - Random fibre distribution with periodicity
  - Interface elements around every fibre



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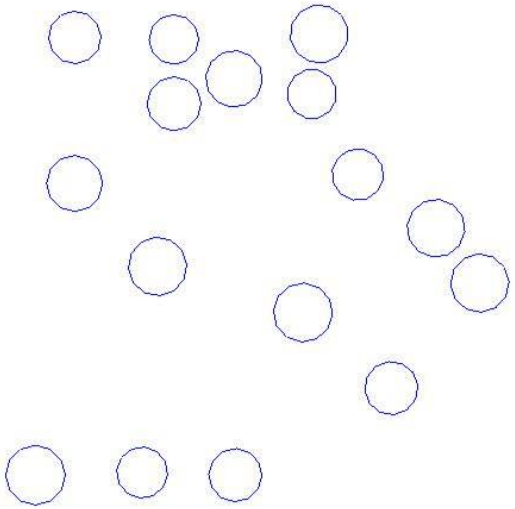

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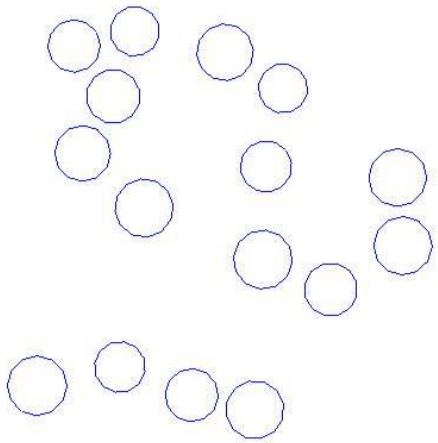

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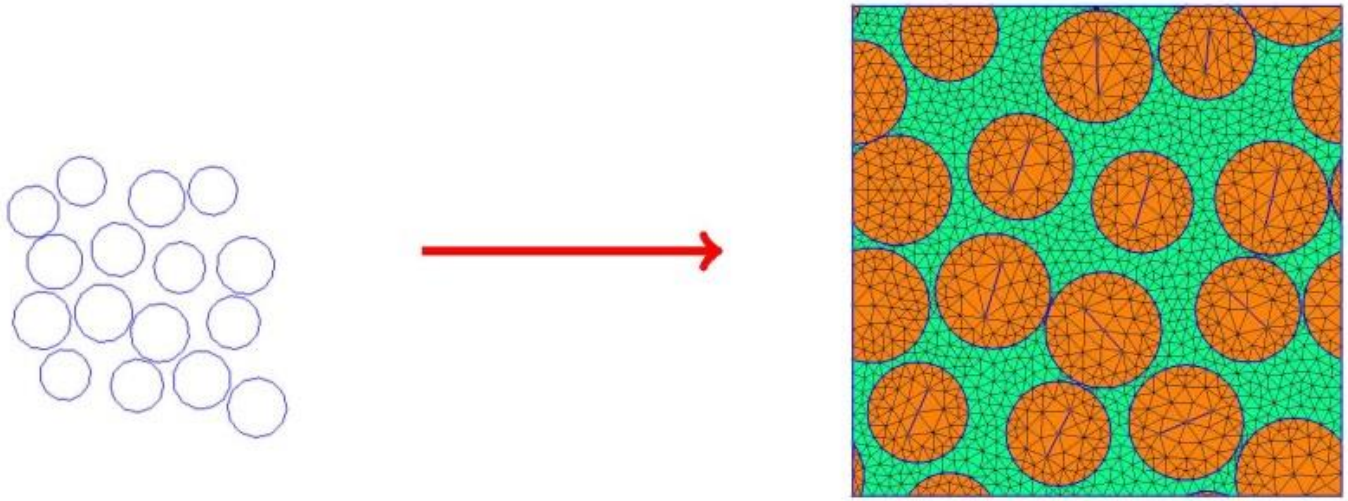
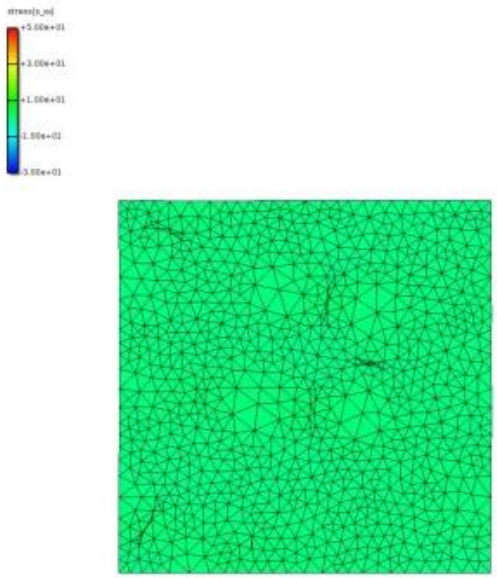


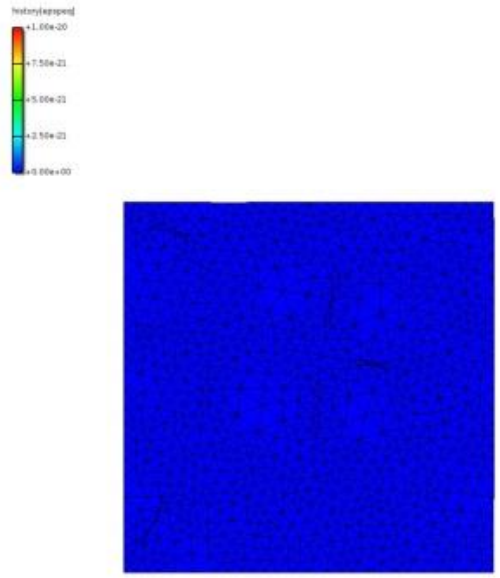
Micromechanical Model

- **Loads and boundary conditions:**
  - Periodic boundary conditions
  - Macroscopic strain applied at corner nodes
  - Swelling strain at every resin point

σ_x[MPa]



ϵ^p_{eq}[-]



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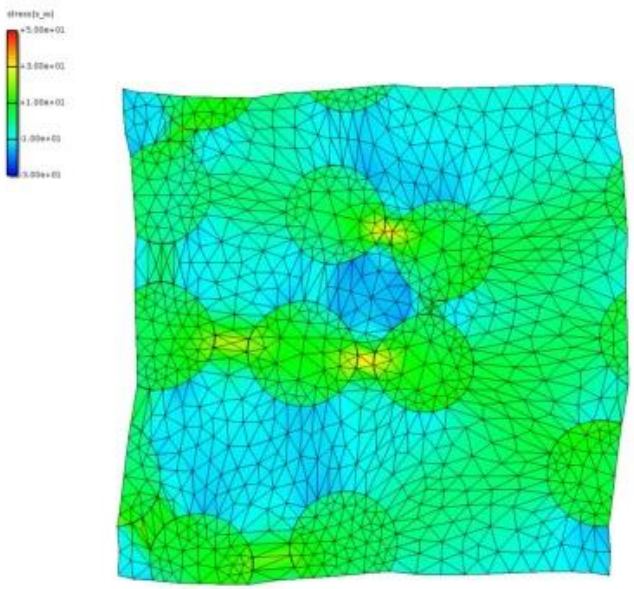

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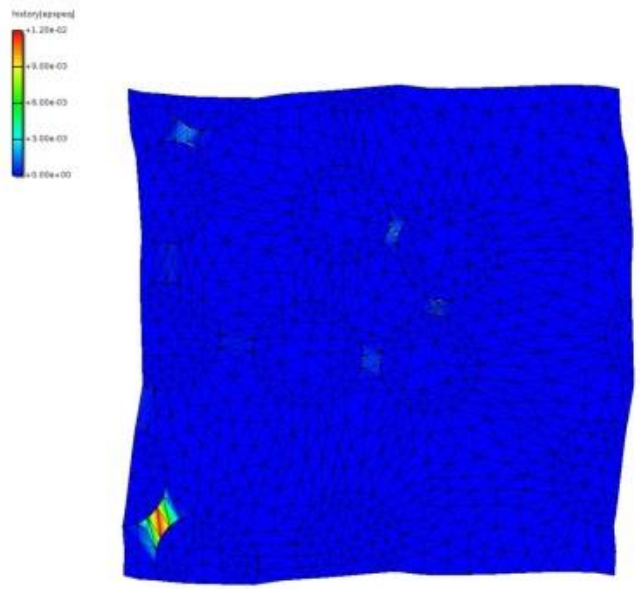

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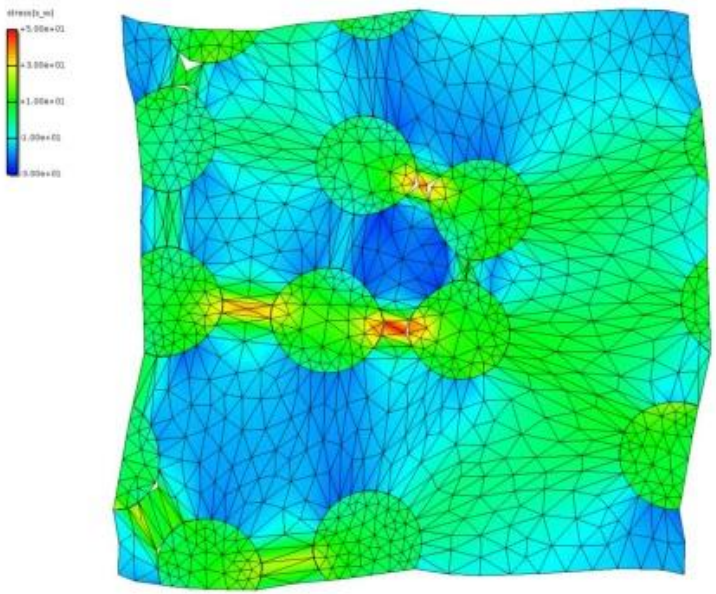

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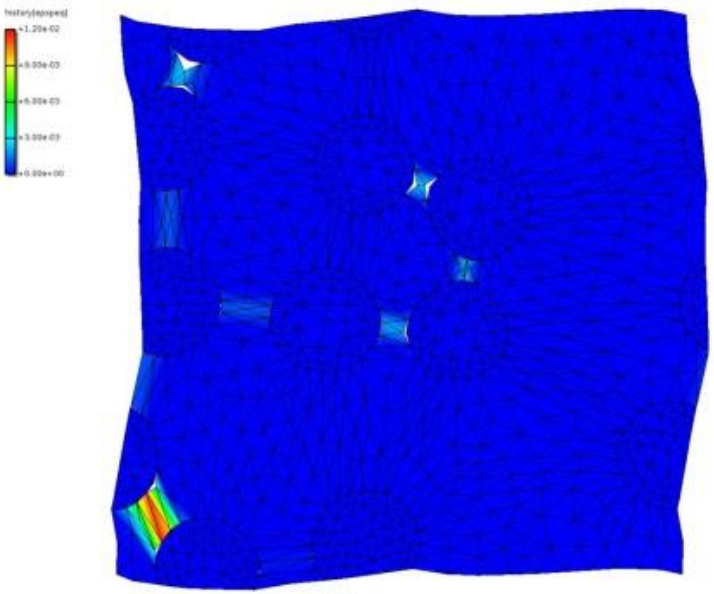
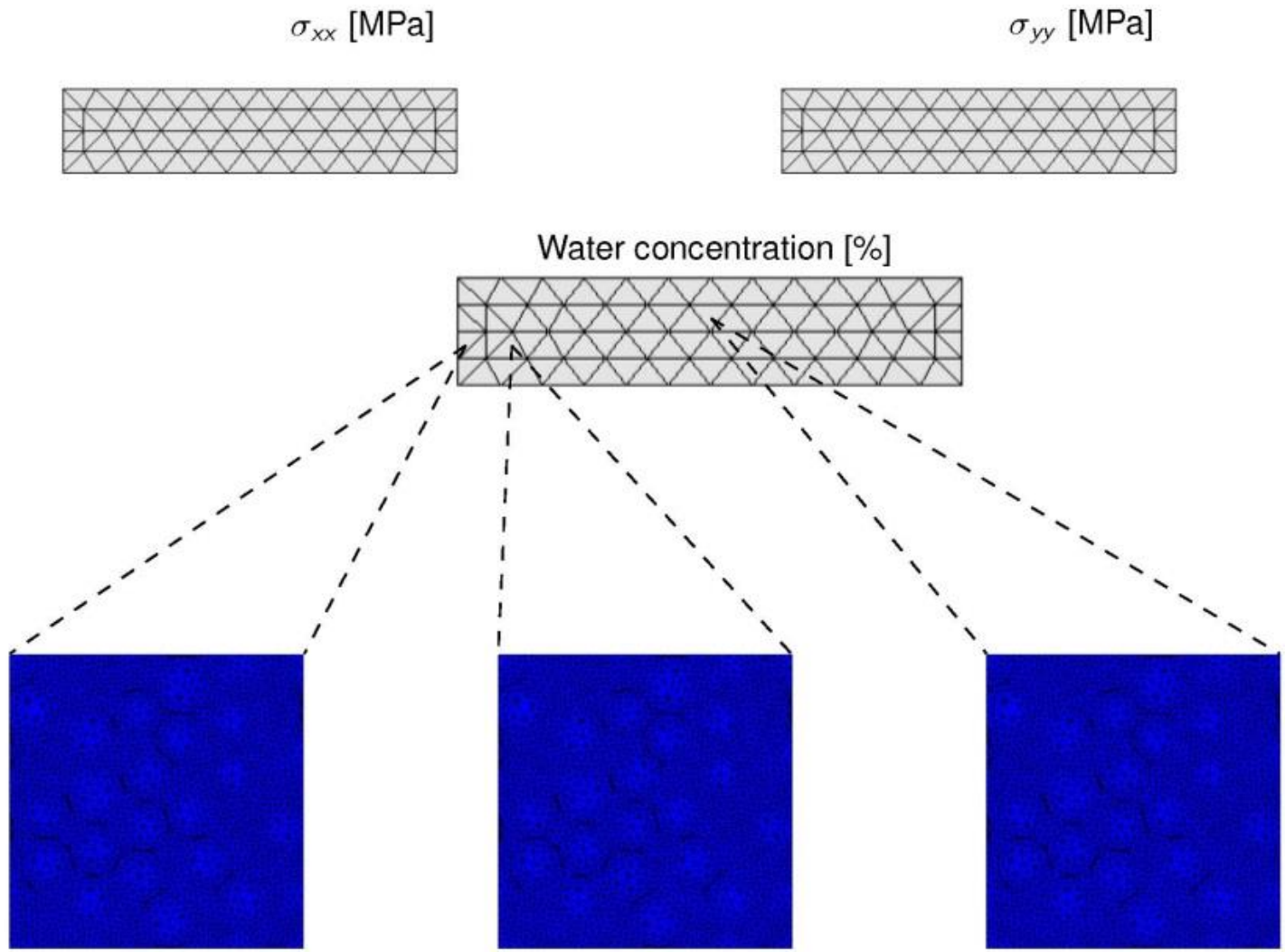


FE^2 Example



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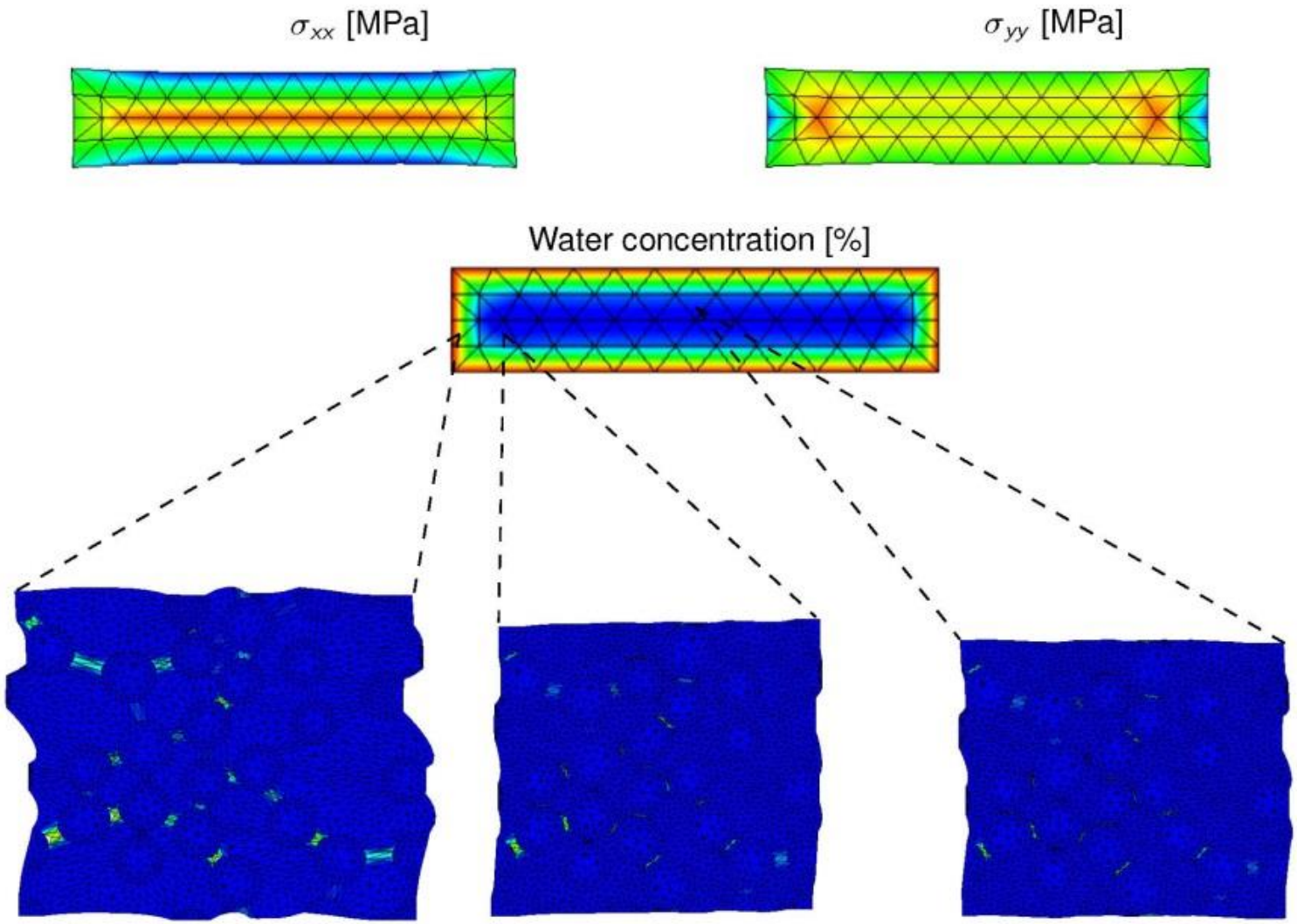

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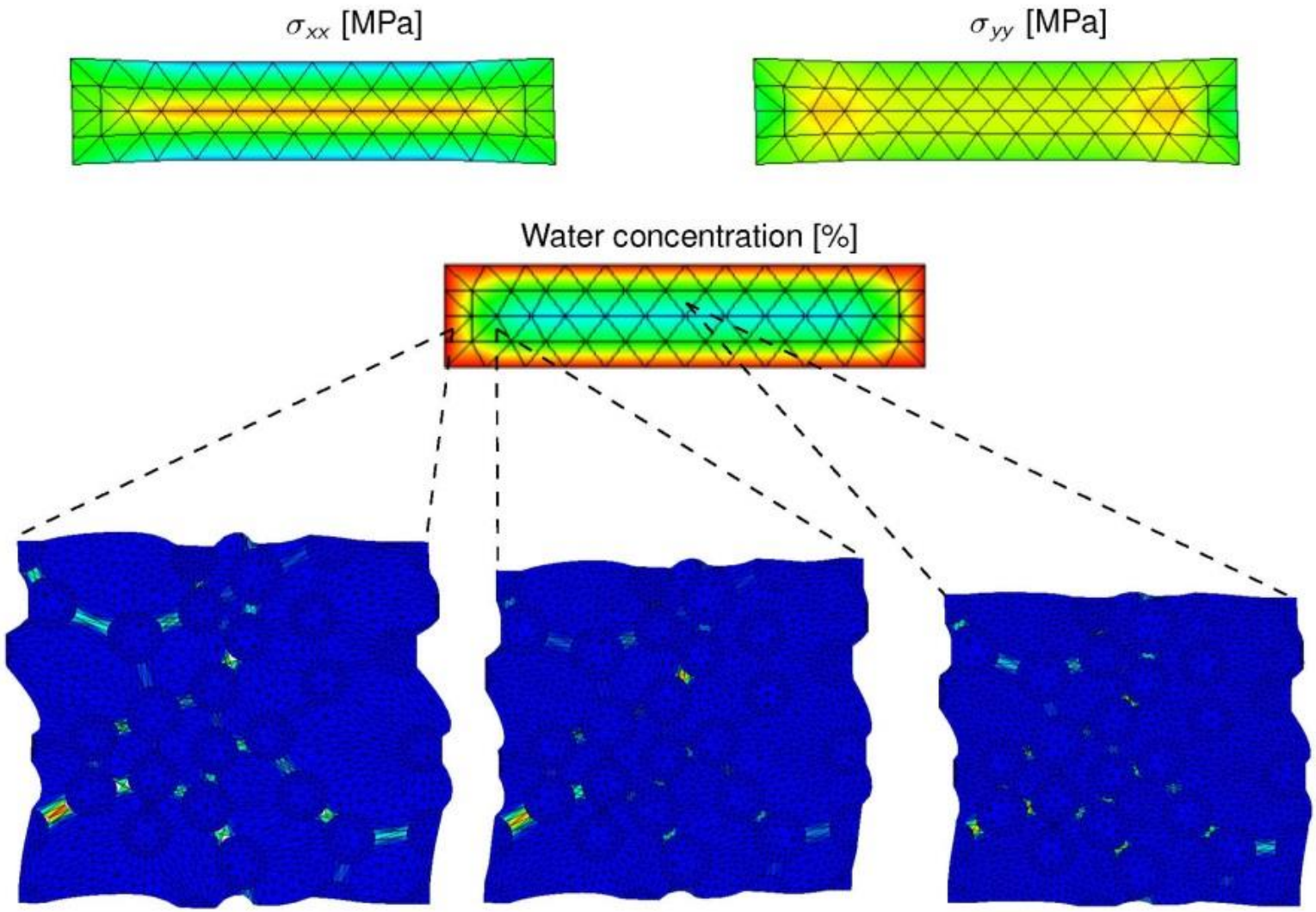

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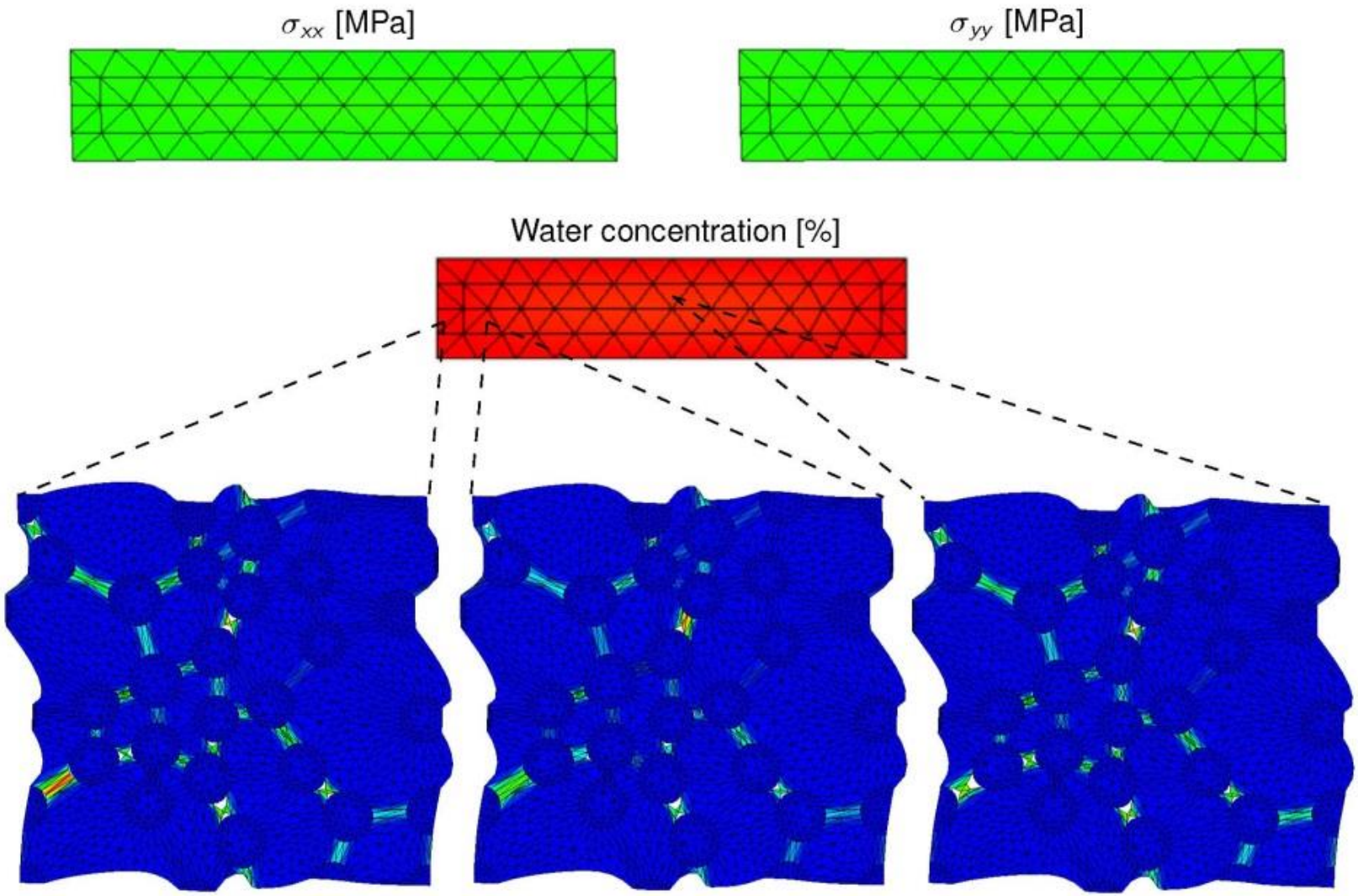
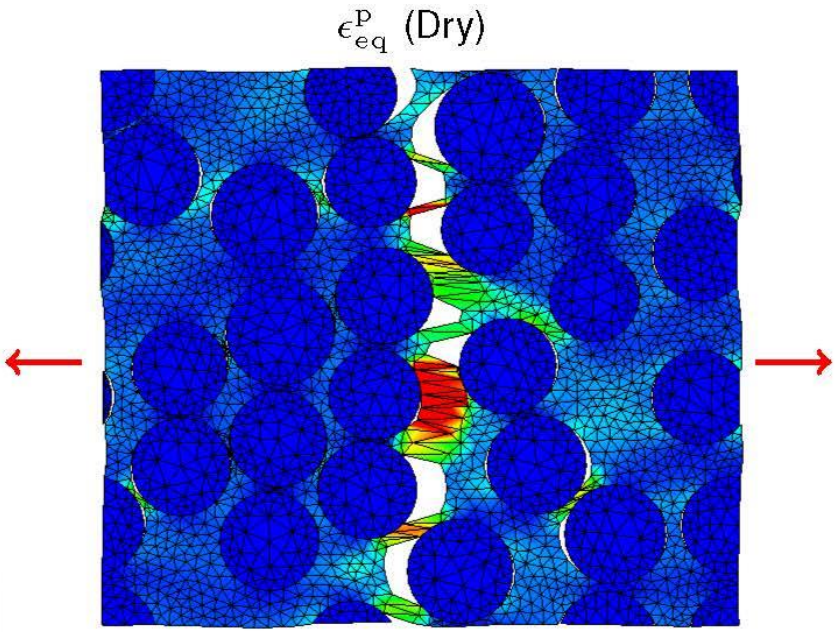
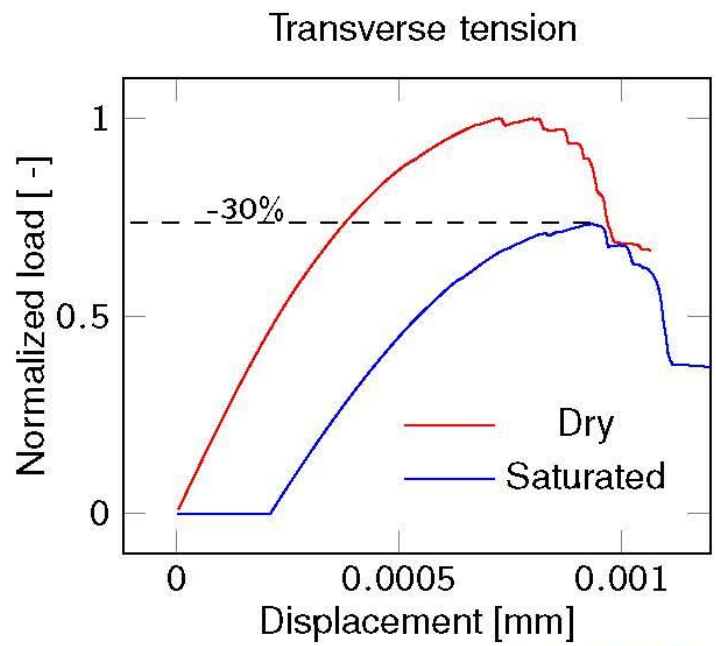


Strength Degradation

- **Loading the final diffusion RVEs:**
  - After saturation, mechanical loads can be applied to the RVEs
  - Crack location changes after immersion





Strength Degradation

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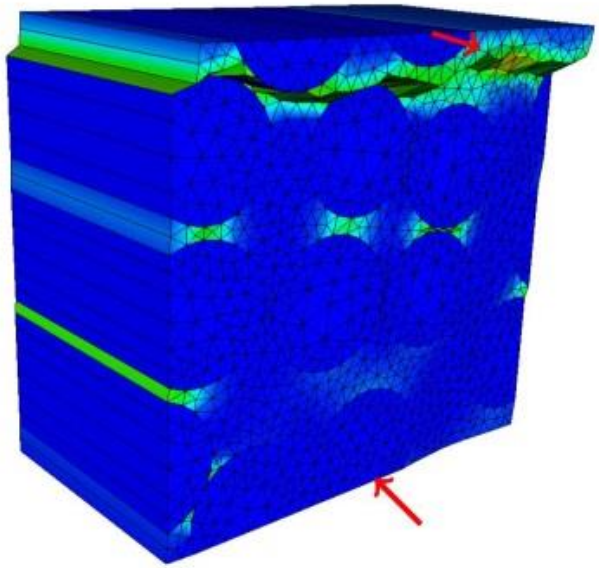
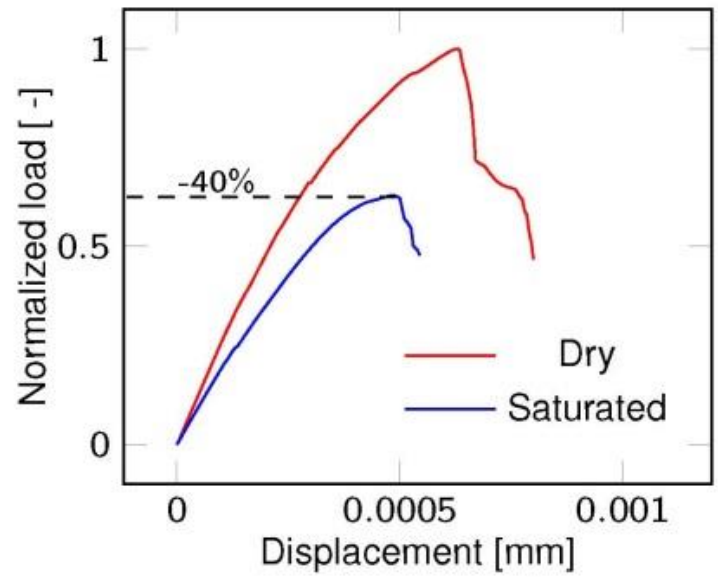
ϵ^{P}_{eq} (Saturated)



Out-of-plane shear



FOCUS6

Integrated Modular Design Tool

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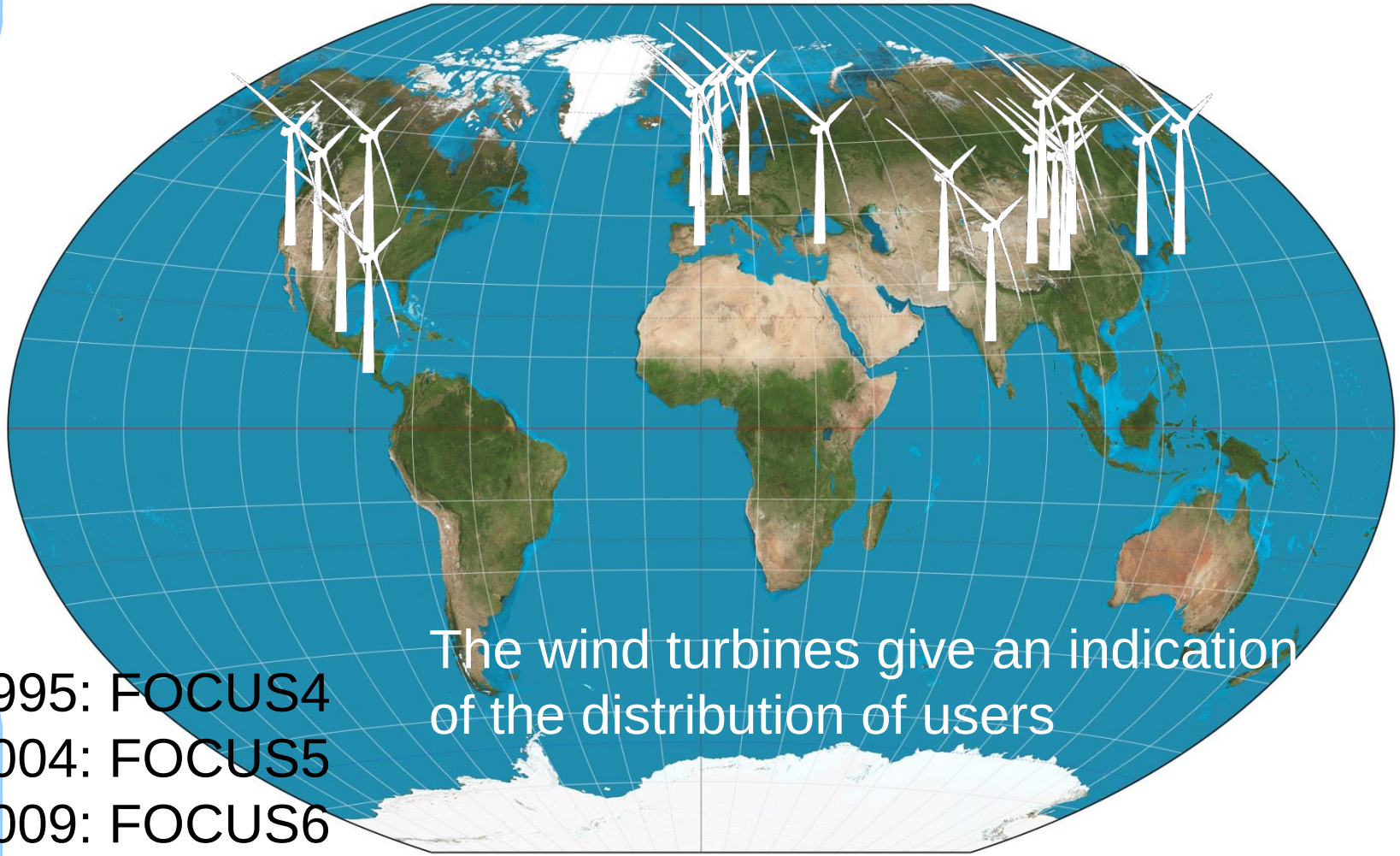
FOCUS across the globe



The wind turbines give an indication of the distribution of users

1995: FOCUS4
2004: FOCUS5
2009: FOCUS6
2016: FOCUS6 version 6.3

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Rotor Pre-Design

- Optimize hydro-elastic performance of the rotor (PV)
- Pre-design optimization of hydrodynamic blade damping of the rotor blades
- Pre-design optimization of eigen frequency, eigenmodes of the rotor
- Based on Blade Element Momentum (BEM) theory

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Structural Blade Design

- **3D interactive blade modeller**
- **Structural analyses**
  - Ultimate Strength, Fatigue and Buckling Strength
  - Modal analysis, Tip deflections
  - Composite failure analysis (IFF, Puck)
- **Visualization of analyses results**
- **External links:**
  - Flex5 and Bladed load set import
  - Export cross-section properties to Bladed
  - FEM export to MSC.Marc, MSC.Nastran, Ansys, Abaqus
  - Blade model export to MSC AdWiMo
  - CAD export in IGES/STEP format

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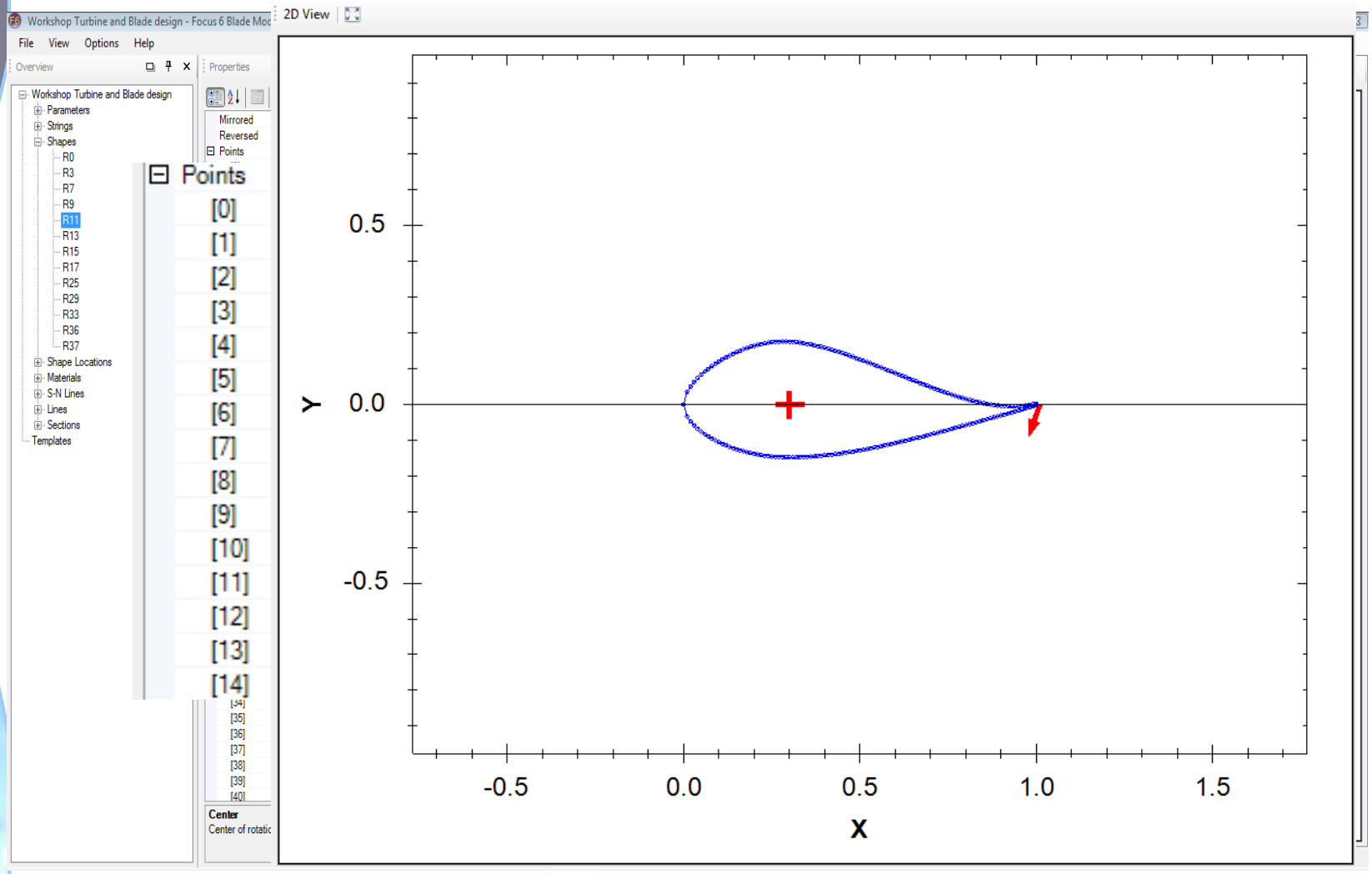
Define Shapes



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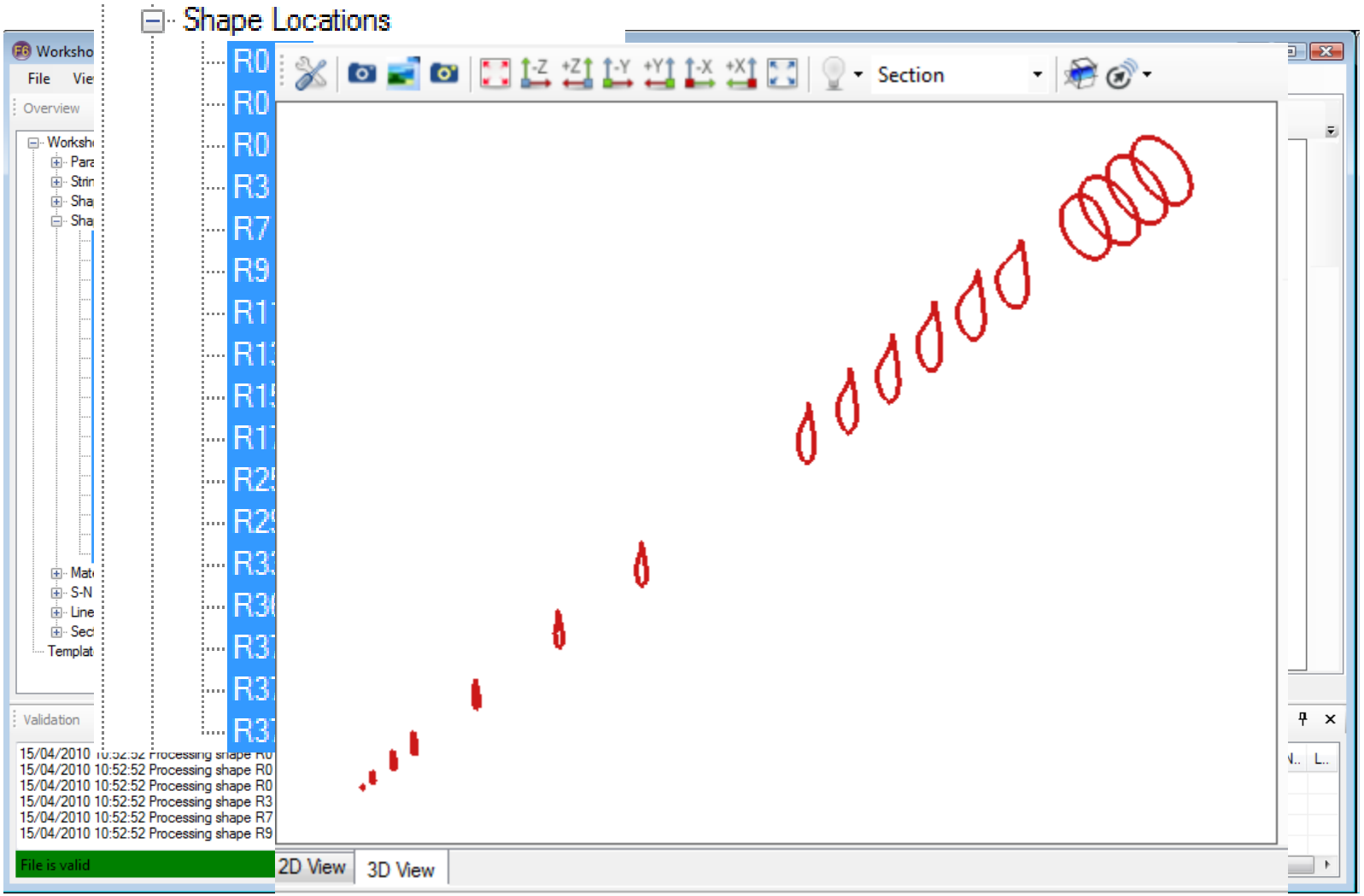
Define Blade: Place Shapes



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Define Material Properties

- Isotropic
- Orthotropic
- Core

- Extra parameters for fatigue formulation

Name	TRIAX
Description	
Material properties	
Type	orthotropic
Density	1.83e-6
E_11	24000
E_22	11000
E_33	
G_12	7200
G_23	
G_31	
nu_12	0.41
nu_23	
nu_31	
FiberAngle	0
E-Modulus (obsolete)	
G-Modulus (obsolete)	
Poisson ratio (obsolete)	
Fatigue analysis	
Constants	...
K	
S-N line name	GL2003
Appearance	
Color	0, 255, 255
Failure data	
Fail_type	none
EPS_T	0.018333
EPS_C	0.014667
TAU	
UTS1_Rk	
UCS1_Rk	

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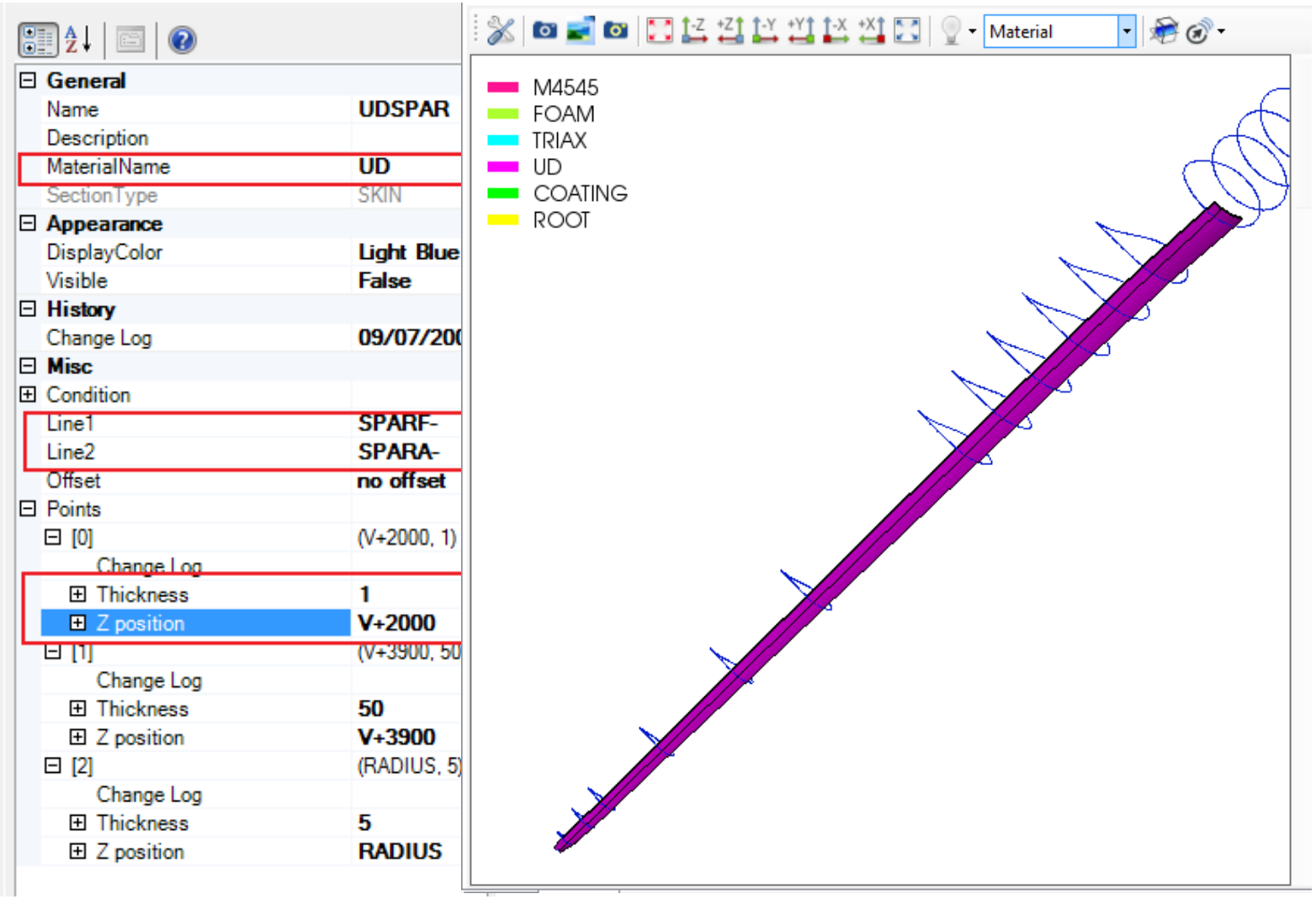
Define Sections



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Blade Design Output

- **Export cross-section properties at selected radial positions for BEM based turbine simulation programs**
- **The usage per material can be exported, e.g. for cost calculations**
- **Export *composite thick shell element mesh* to:**
  - FOCUS for Blade Design
  - ANSYS
  - MSC Marc
  - MSC Nastran
  - Abaqus (2014)
- **Ultimate/Fatigue reserve factors**
- **Deflections**
- **Eigen modes / frequencies**

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Turbine Design

- Calculates the hydro-dynamic and structural dynamic behaviour of a tidal turbine in the time domain
- Power curve and hydro-elastic performance
- Tower model included (monopile, simple tripod)
- Alternatively use advanced tower models via the Craig-Bampton method
- A built-in PD pitch controller
- Built-in supervisory controller
- External dedicated pitch controllers can be used
- Apparent mass

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Load Set Calculations

- Load-cases according DNVGL-ST-0164
- Simulate fault conditions and emergency situations

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Tidal

- **Tidal stream turbine simulator**
- **Generator combines**
  - Wave models
    - Frequency spectrum
      - Jonswap
      - Pierson-Moskowitz
    - Non-linear regular waves
  - Current
    - Shear: log, power law, user-defined
    - Wind-induced
  - Turbulence

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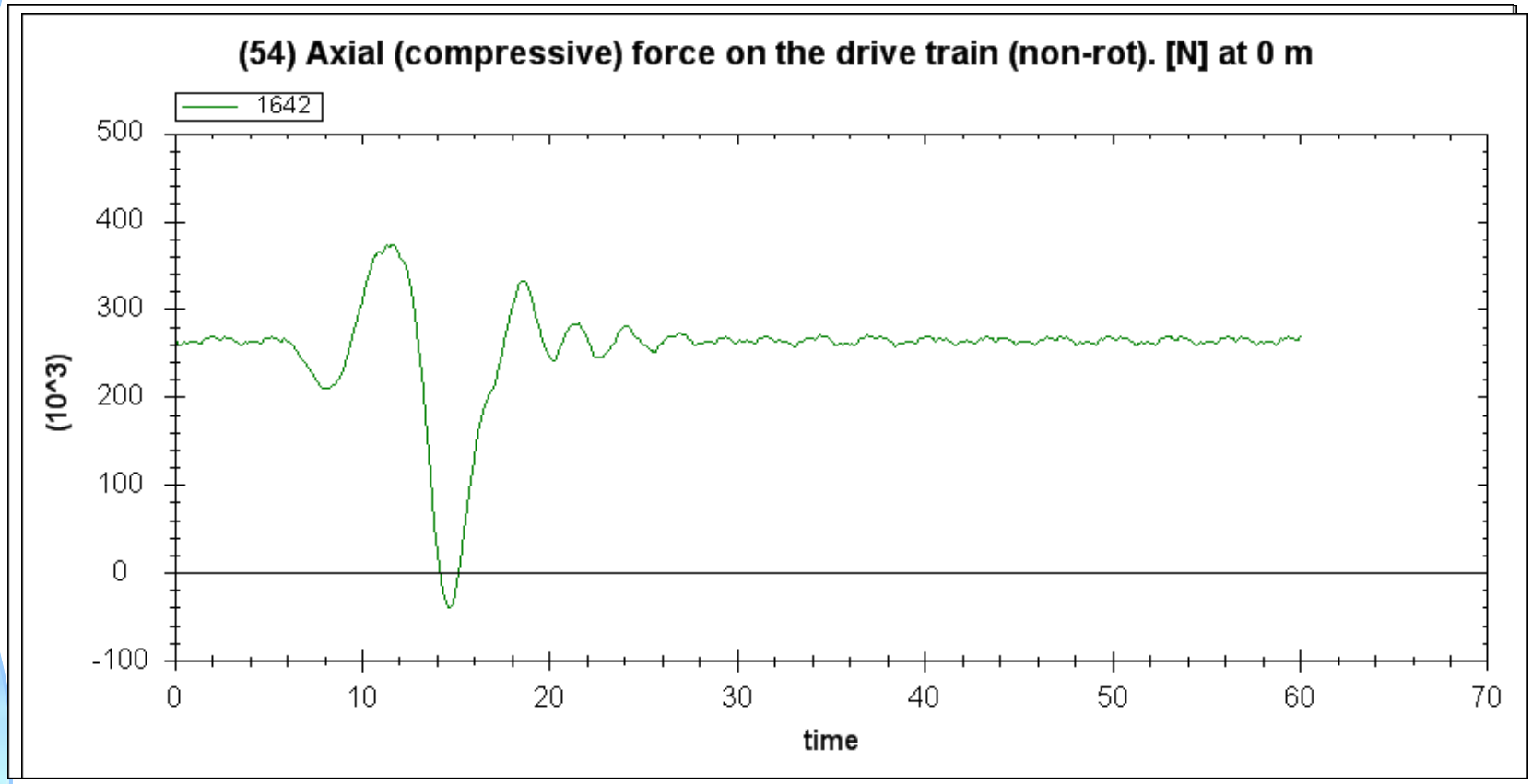
Aero-Elasticity II, Plotting

Extreme operating gust (50 years at rated wind)



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Postprocessing Load Sets

- Extreme load reports (GL 2005 Annex 4B)
- Load roses
- Fatigue equivalent loads
- Time-at-level counting for bearings etc.
- Load spectra
- Load set summary (e.g. minimum tip clearance)

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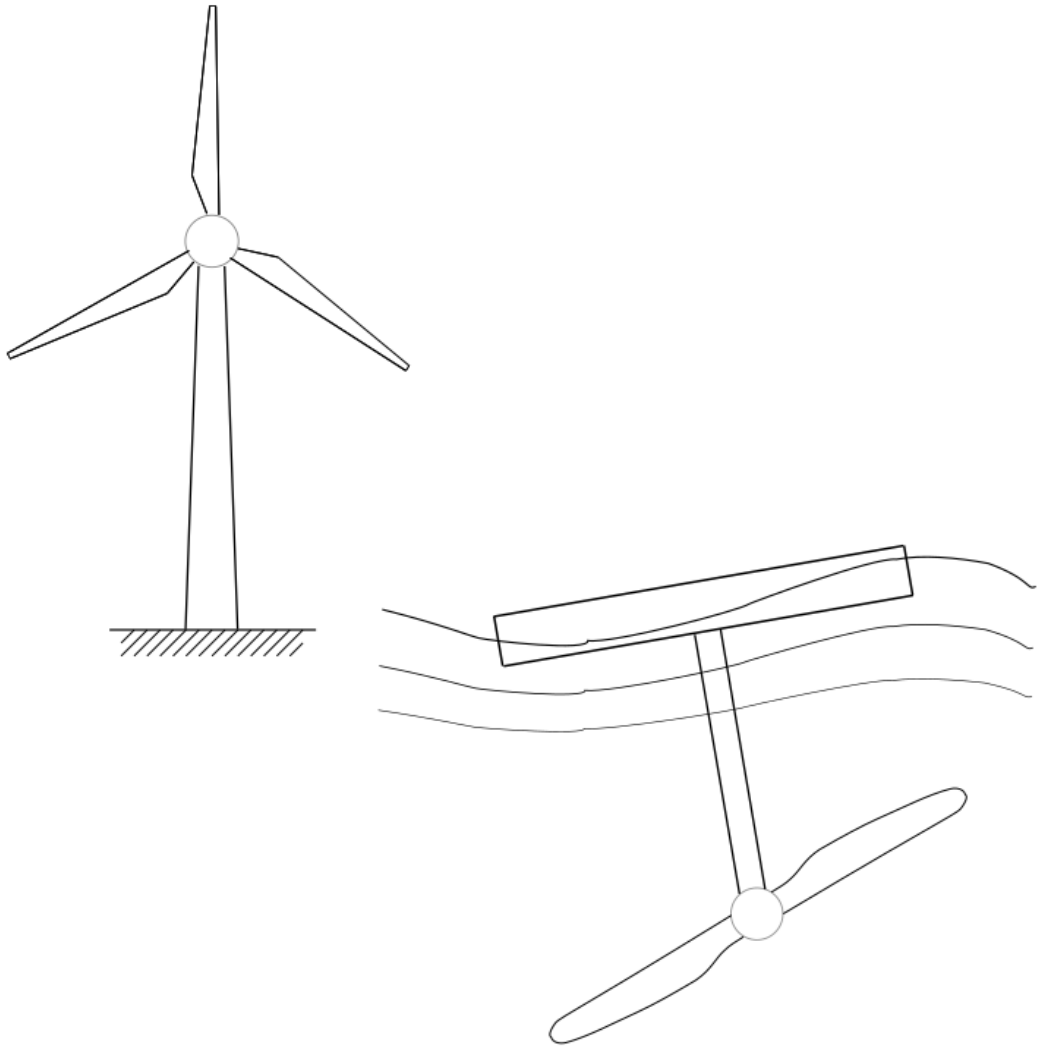
Floating tidal turbines



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Video of tidal turbine simulation

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