Simcenter 3D Virtual Material Characterization ToolKit

for realistic composite materials modeling using micro-CT-based voxel approach

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Stepan V. Lomov, Martine Wevers (KU Leuven)

Outline

- Vision towards engineering with composites
- Simcenter 3D and VMC ToolKit for virtual material characterization
- Idealized vs realistic geometry of composites
- Micro-CT voxel-based modeling approach
- Applications and challenges

Composite design at Honda R&D Co., Ltd.
Enabled by multi-scale approach

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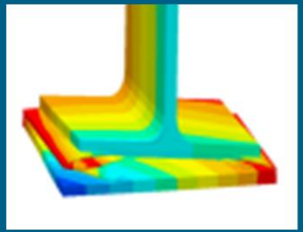
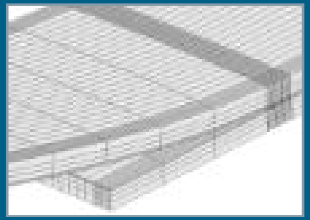
Vehicle
Expertise build-up
full vehicle simulation

Subsystem
Validation of complex
subsystem modeling



Component
Model validation on
components
and joint technology



Coupon
Design/Validation
of material models

Multi-scale simulation

Frontloading
Composite design
to maximize
design space
exploration
(Multi-attributes)

"We need more simulation-based product design data and coupon level testing to establish a dependable simulation process for all the material and design choices at hand."
Dr. Yuta Urushiyama, Chief Engineer, Technology Research Division, Honda

The vision - towards engineering with complex materials
Supporting manufacturing and performance decisions

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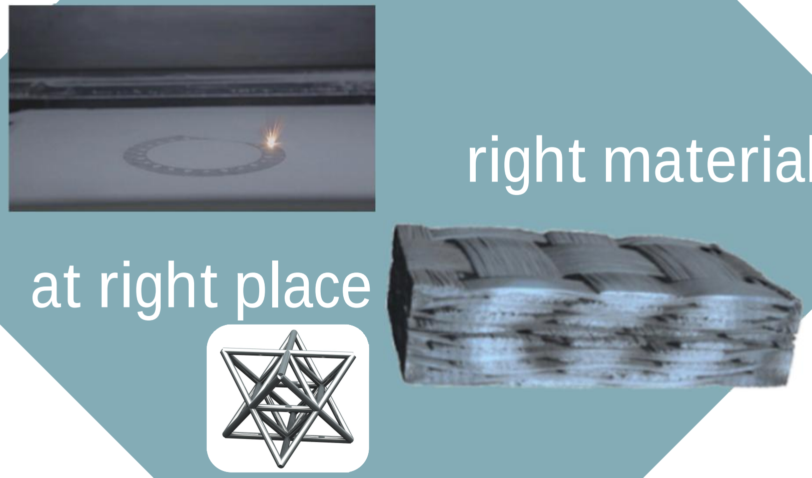
Multi-Material

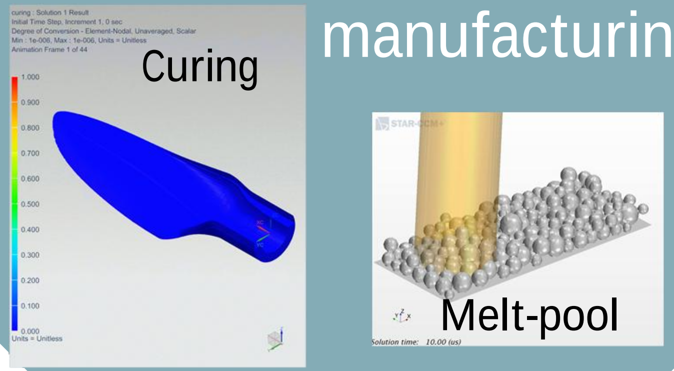
right material

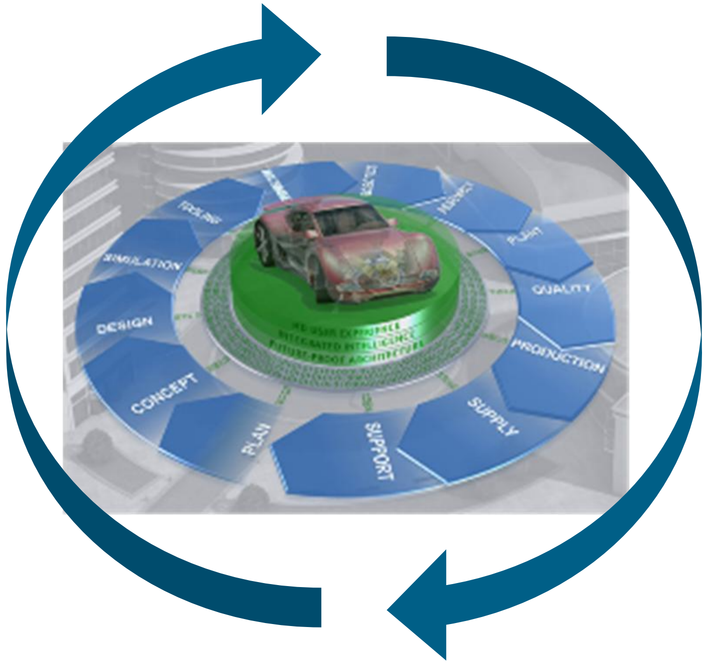
at right place



Multi-Physics

manufacturing



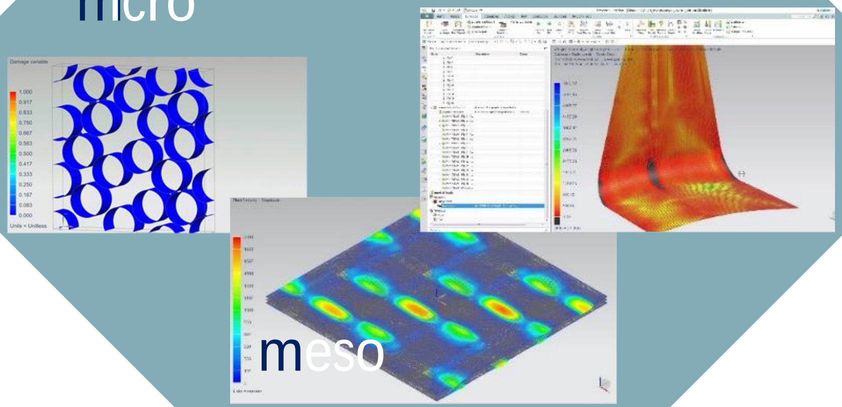


PLM - process linking and data management

Multi-Scale

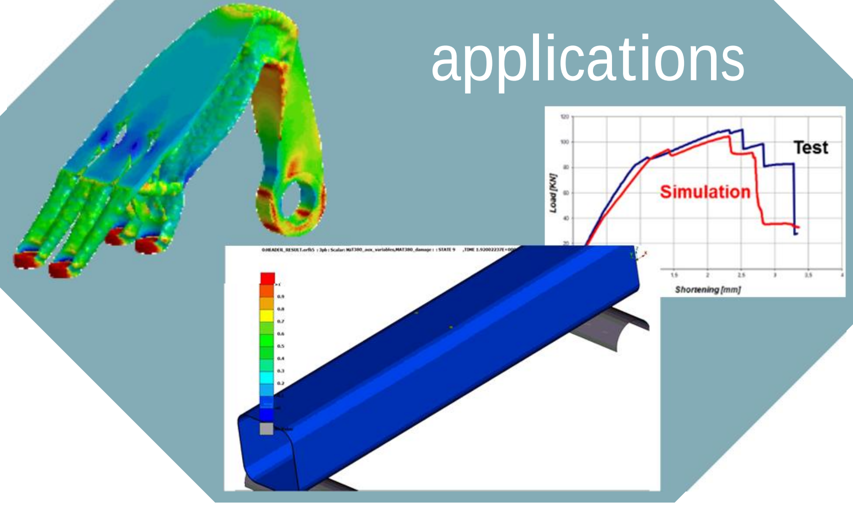
micro

Macro

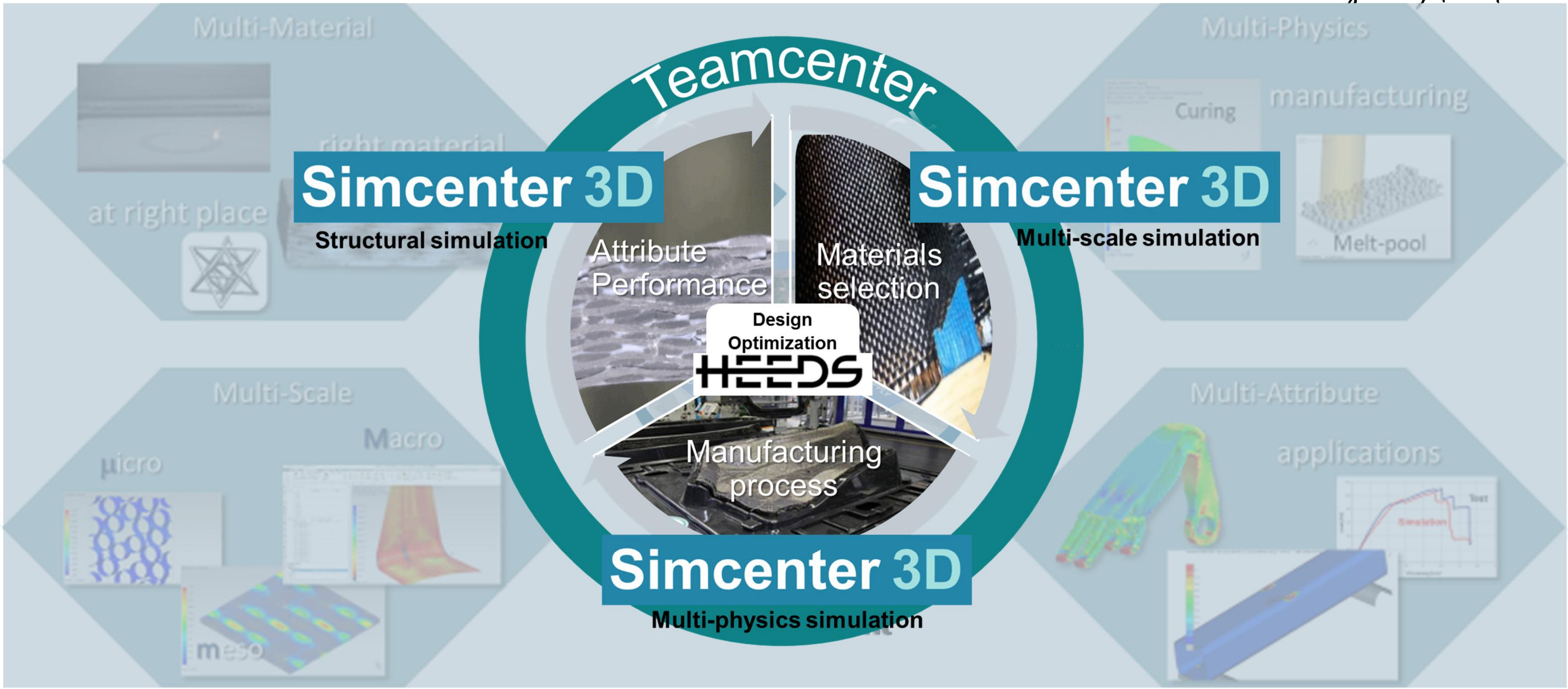


Multi-Attribute

applications

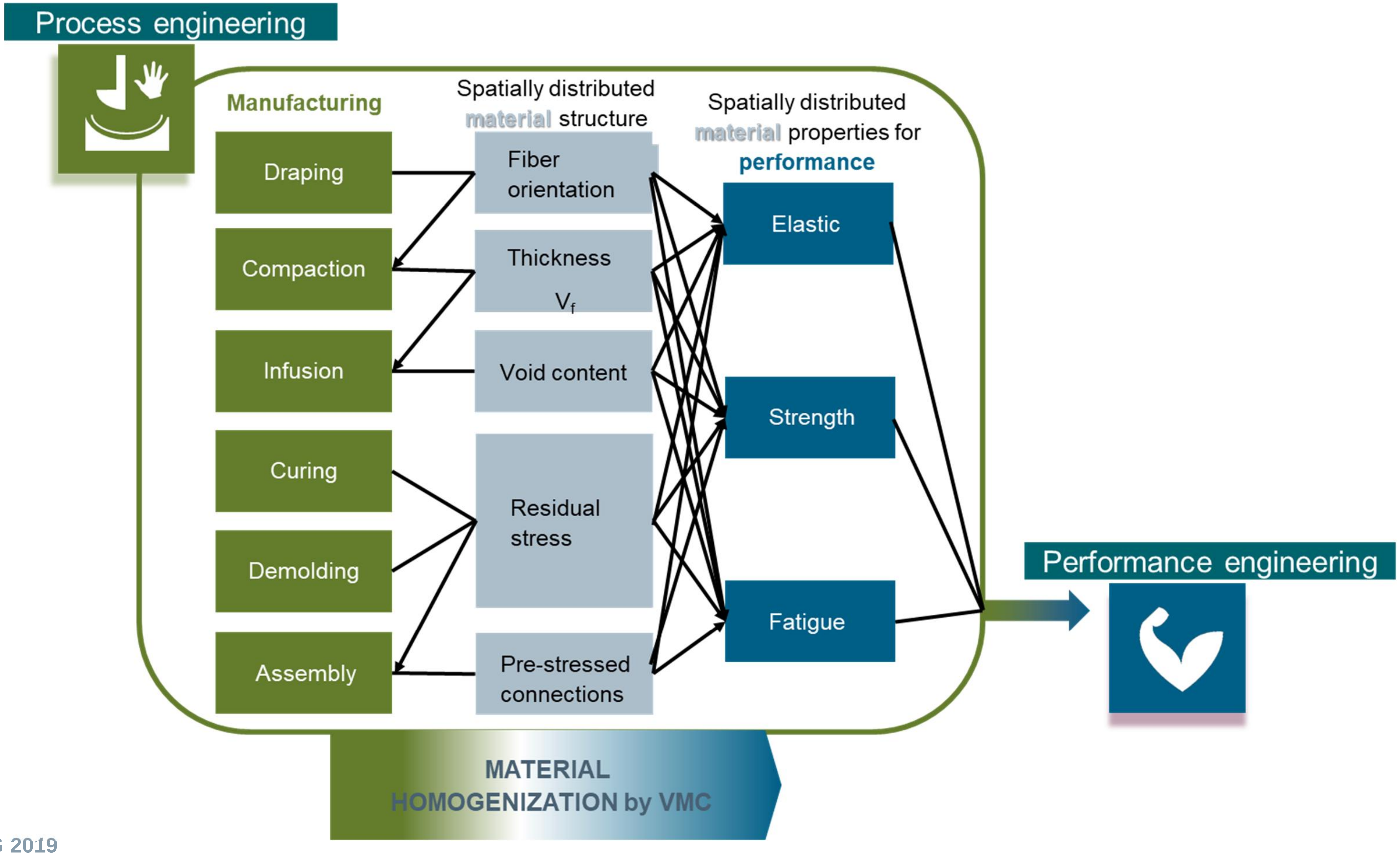


The vision - towards engineering with complex materials
Supporting manufacturing and performance decisions



1. Create high-value and validated engineering workflows

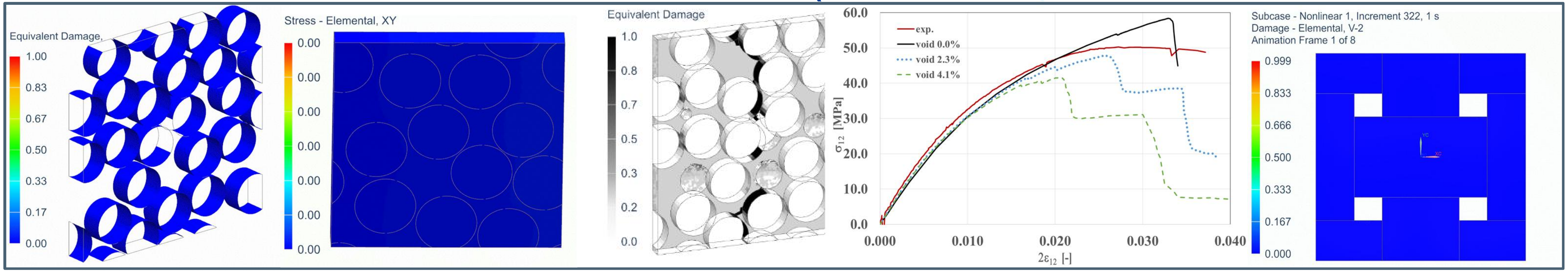
From process to part performance engineering



Key is multi-scale simulation and homogenization

Managing a puzzle of multi-physics simulations in Simcenter 3D

Mechanical simulations (Simcenter Samcef)

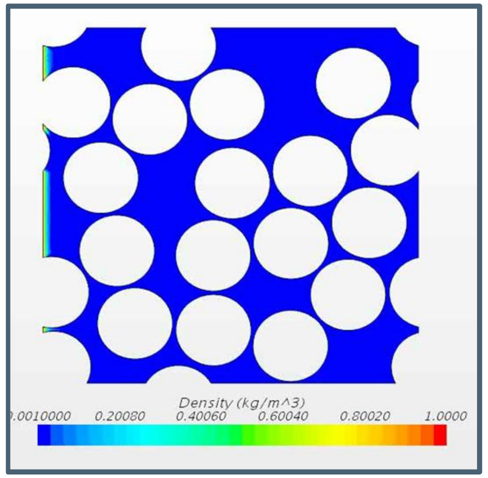


→ *Damage-plasticity parameters (Ladeveze)*

→ *Effect of voids*

→ *Damage evolution*

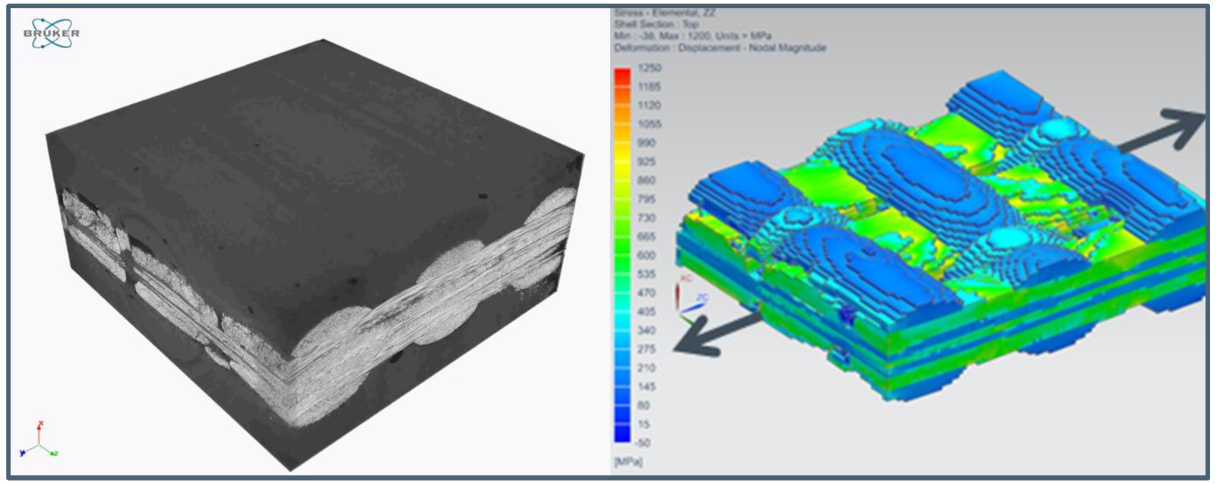
Flow simulation STAR-CCM+®



→ *Permeability*

→ *Void content*

Realistic models (Multi-solver support)



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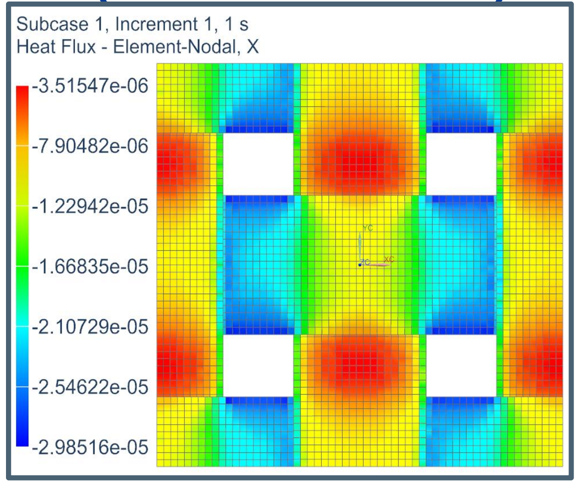
→ *Create models based on micro-CT scans*

Thermal simulation (Simcenter Samcef)

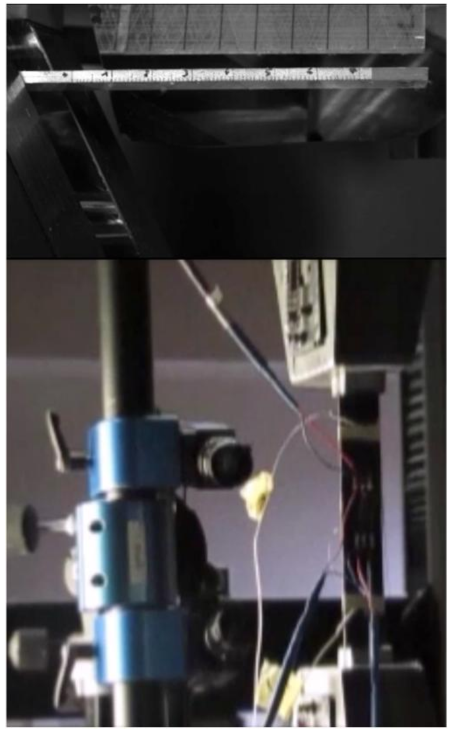


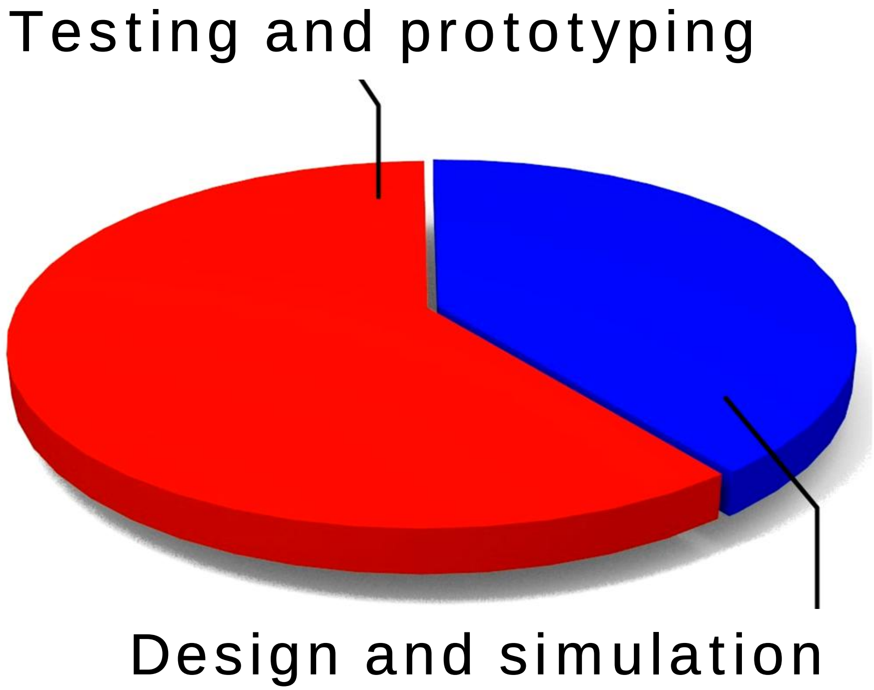
→ *Thermal conductivity*

2. Virtual Material Characterization (VMC)

to accelerate composite material engineering

Test Based

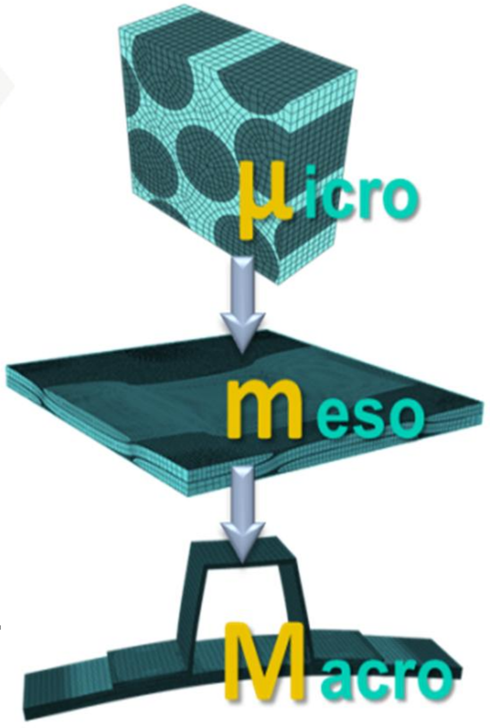




Motivation

Large number of parameters (fiber/matrix/interface properties, material architecture, stacking)

à large and **expensive test campaign** (100’s of coupon tests for multi-attribute characterization)



- ü **Reduced number of tests**
- ü Considering **performance** and **manufacturing-related aspects** (effect of defects)
- ü Enabling **multi-attribute virtual material optimization**

WHAT is VMC (Virtual Material Characterization) Toolkit

Simcenter 3D and the VMC ToolKit vertical app

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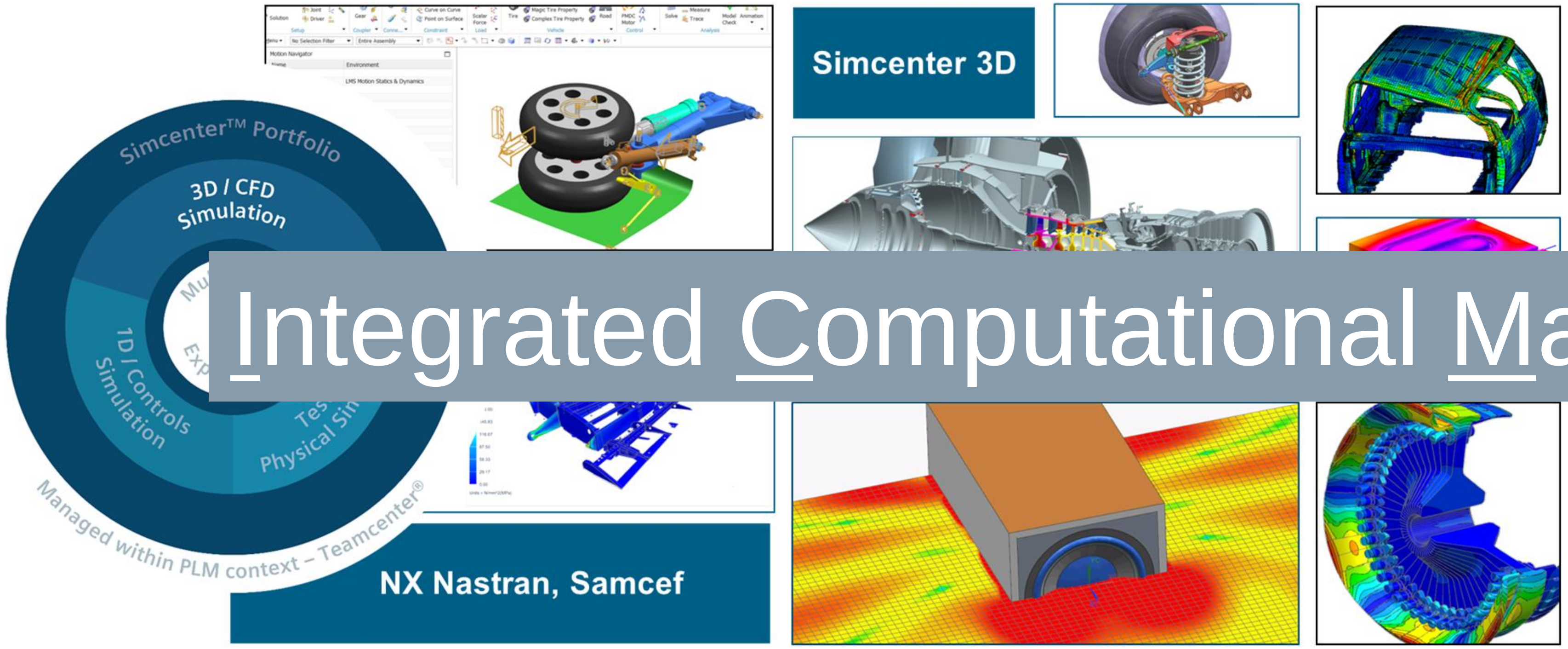
Multi-attribute, multi-physics CAE environment

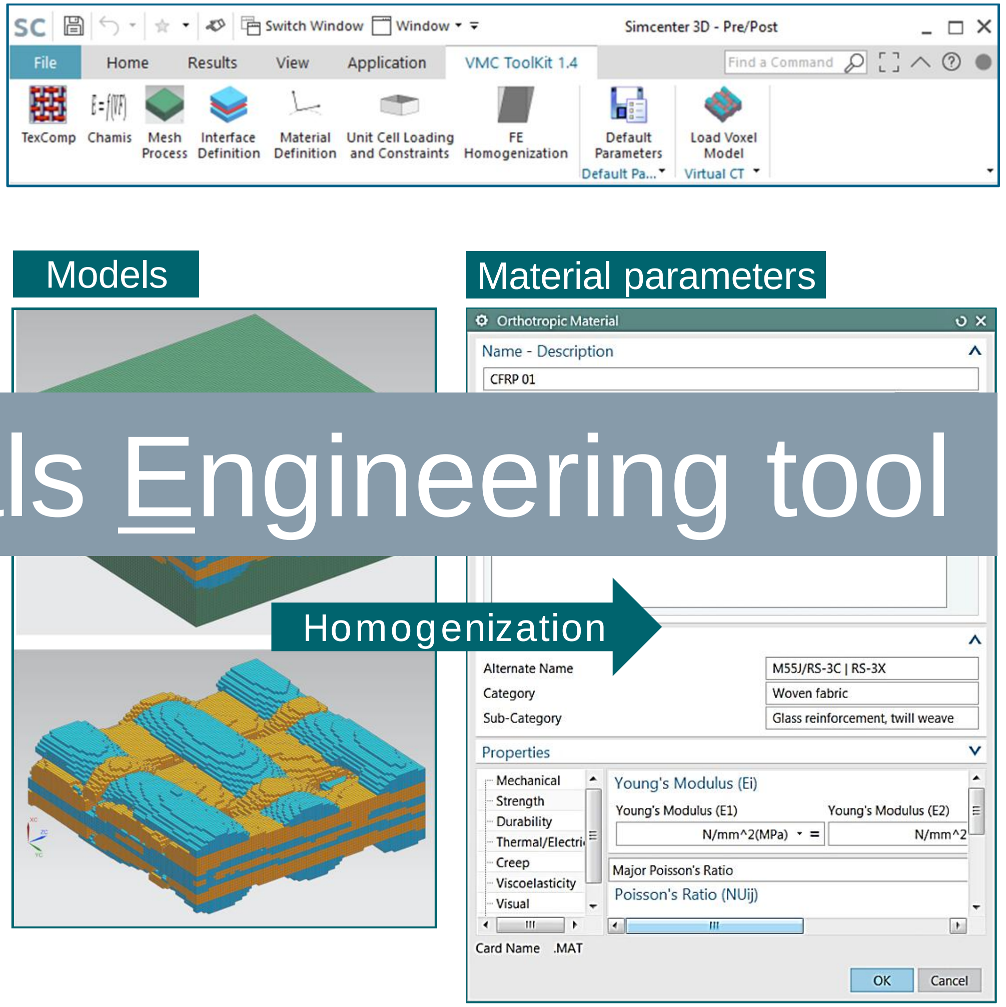


VERTICAL APPLICATION

Integrated Computational Materials Engineering tool

4th release available

VMC ToolKit in Simcenter 3D



VMC ToolKit

Composite properties and workflow

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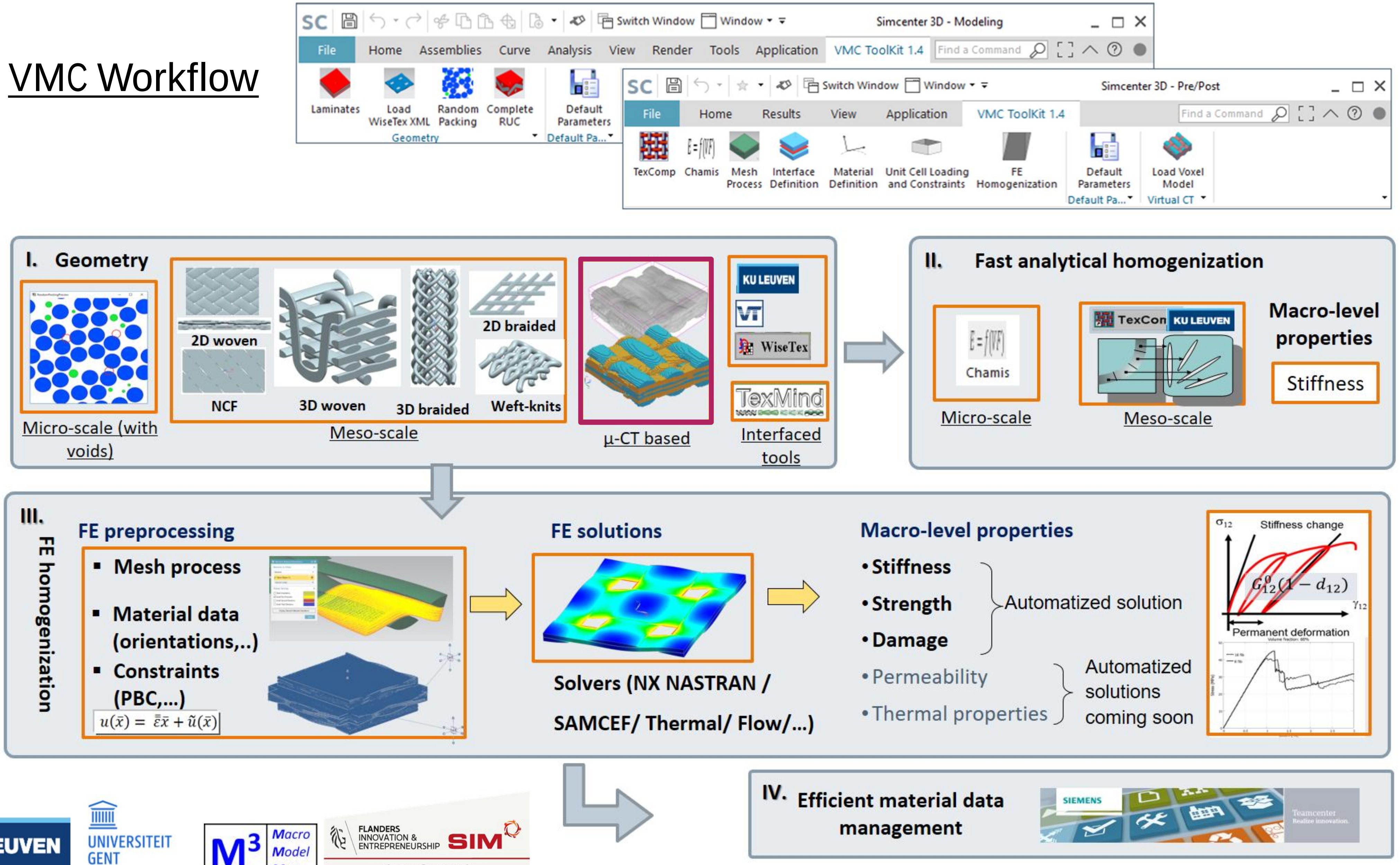
VMC Toolkit for multi-physics

- Mechanical properties
  - *Stiffness*
  - *Strength*
  - *Damage*
  - *Dry-fabric mechanics (forming)*
- Thermo-mechanical assessment
  - *Residual stresses/ deformations (curing)*
  - *Thermal conductivity*
- Flow properties
  - *Saturated permeability (for infusion)*
- Multi-solver support
  - *Simcenter Nastran*
  - *Simcenter Samcef*
  - *Simcenter Thermal/Flow*
  - *...*

VMC Workflow



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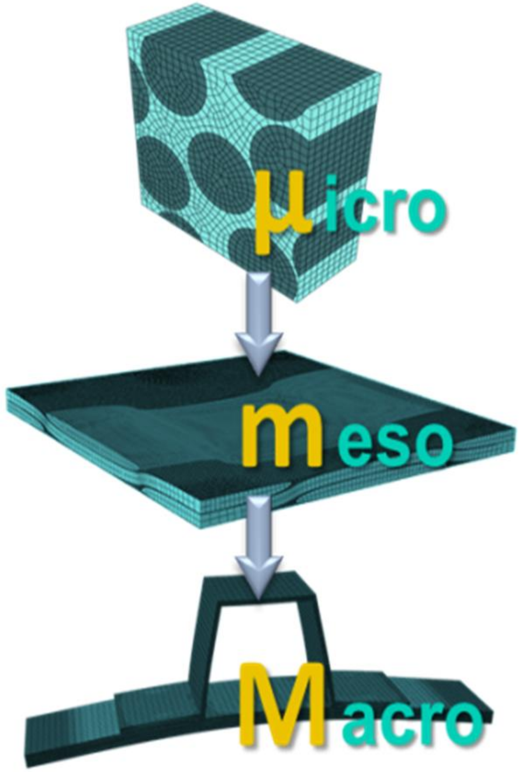
Composite unit cell geometry generation
Meso-scale representation

The **unit cell (UC)** is a "building block" of the composite material



Idealized UC structure

ü *Generators:*
- v *WiseTex by KU Leuven,*
- v *TexGen by University of Nottingham*

ü *Assumptions on simplified shape of the yarn cross-section, its constant form along the yarn length or warp/weft yarns alignment*

ü *Efficient model generation*

ü *Do not consider variability and possible defects*

ü *Interpenetrations can be observed*

Real geometry

ü *Can be visualized using micro-CT*

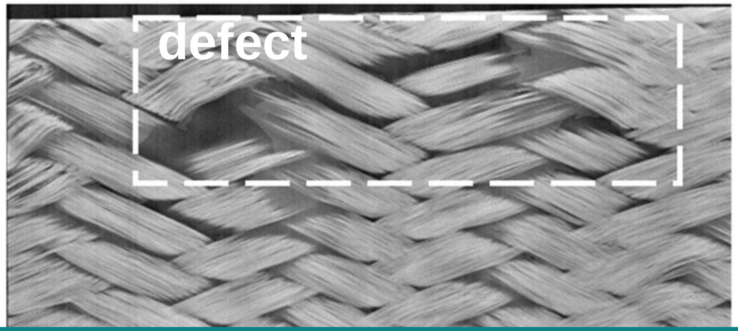
ü *"As-manufactured" including geometrical variability and defects*

ü *Interpenetration-free, mesh is created*

ü *Relatively slow: time-demanding image acquisition and processing*

ü *Resolution limitations: ratio between the studied feature and voxel size*

ü *Challenges related to geometry extraction (segmentation) exist*



more reality (details) in the modeled geometry → higher accuracy of the prediction

VoxTex software by MTM, KU Leuven
Quantification of micro-CT images of textile composites

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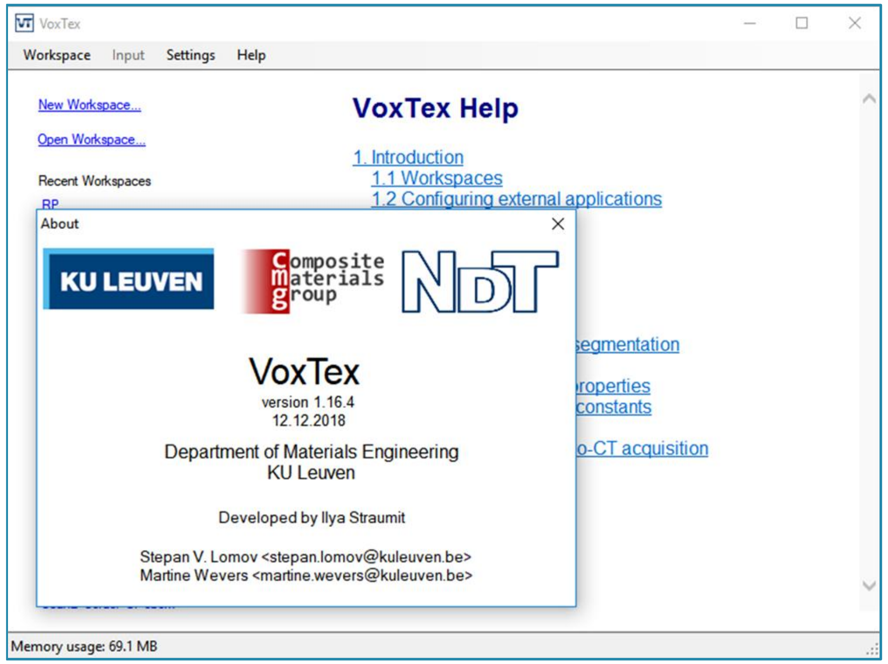
INPUT: *GE Nanotom volume file or TIFF/BMP image stack (other CT-scanners)*



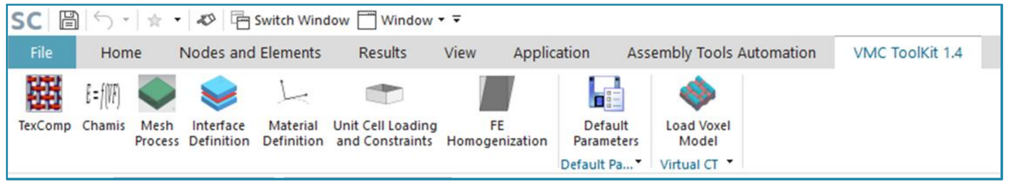
based on the structure tensor

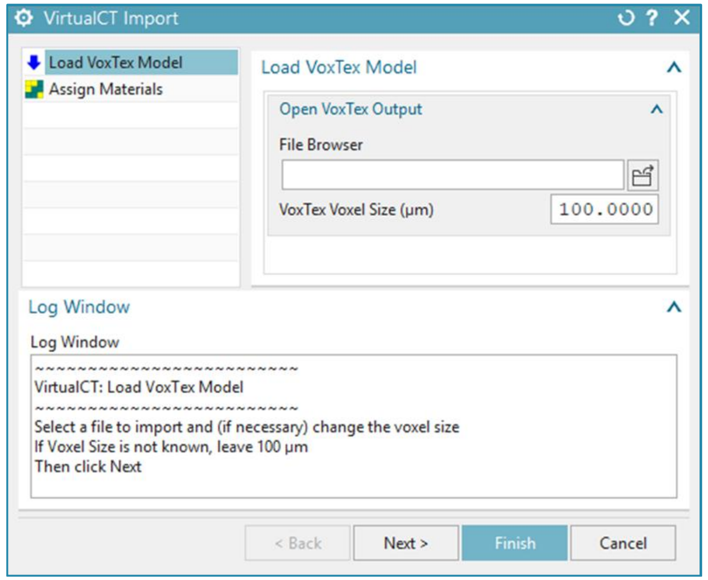
11 September 2019
Session 3
Prof. Stepan V. Lomov
KU Leuven "Micromechanics of Fibrous Composites and Permeability of Fibrous Media Based on Micro-CT Images"

OUTPUT
ü Visualization: ParaView
ü FEA: Abaqus and **Siemens Simcenter 3D**
ü Permeability: FlowTex and Homogenization: TexComp (WiseTex Suite, KU Leuven)

Simcenter 3D

interface with VoxTex for VMC ToolKit called "VirtualCT"





VirtualCT for VMC ToolKit

Workflow: from micro-CT images to material properties

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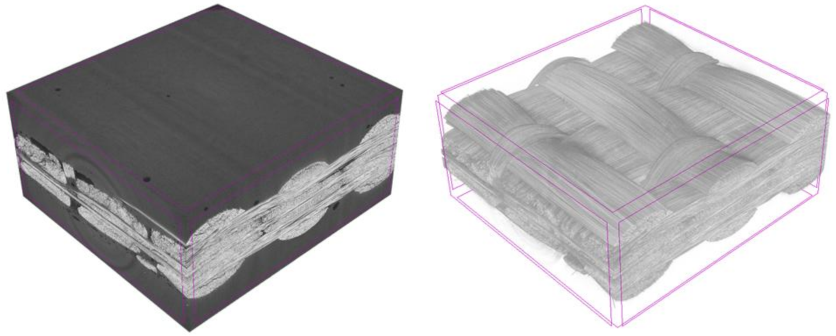
micro-CT volumetric image



Supervised segmentation and orientation analysis
VoxTex (MTM, KU Leuven)

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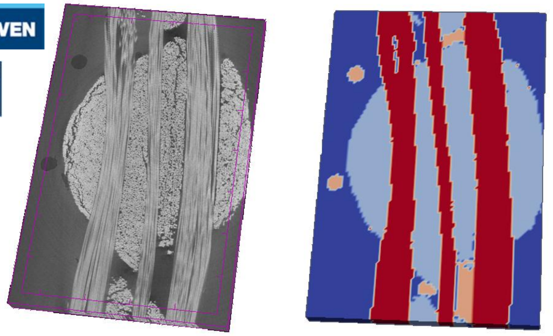
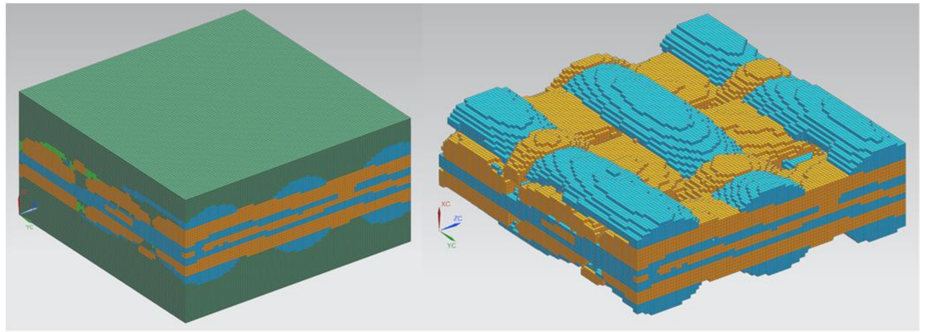
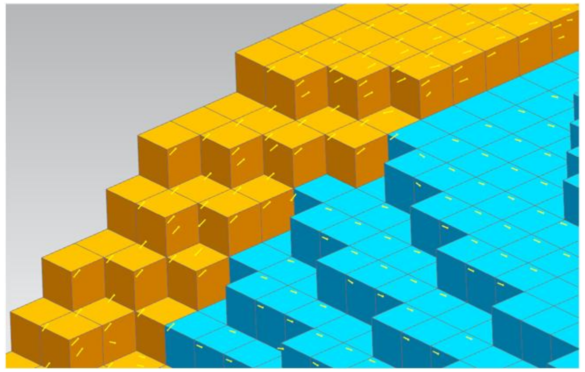


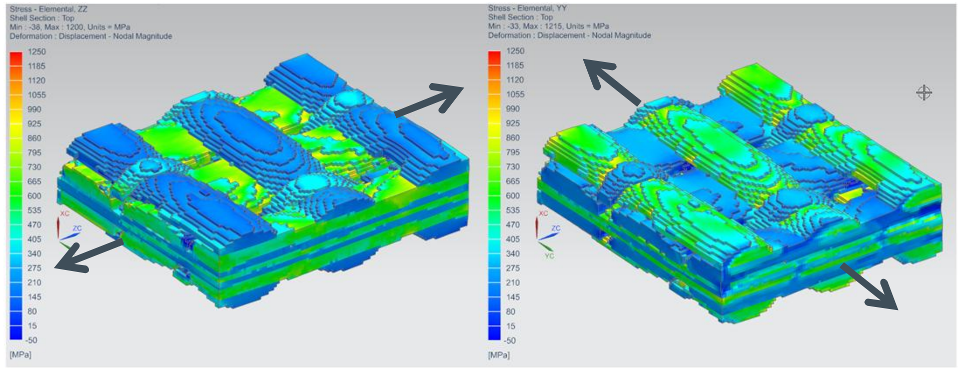
Import to Simcenter 3D as a voxel model



Local material orientations
are included



Virtual testing with VMC ToolKit
stress shown in the direction of the load (2 cases)



FE homogenization
full set of the elastic constants:

- Young's moduli
- Shear moduli
- Poisson's ratios

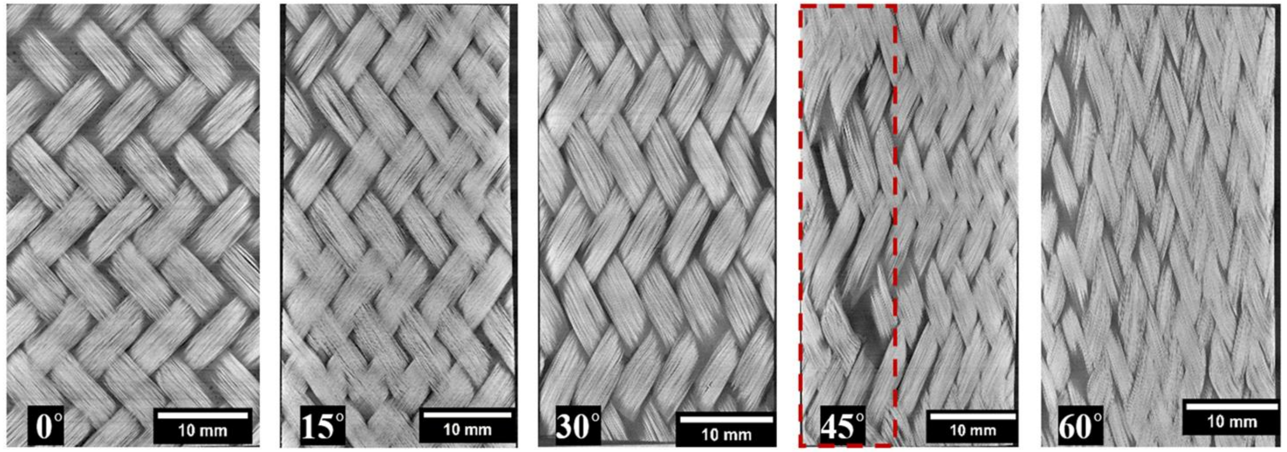
Results

☐ Rotation Around Z Axis	
Mass Density (RHO)	1.7295929276: kg/mm
Young's Modulus (Eii)	
Young's Modulus (E11)	7066.2753866 MPa
Young's Modulus (E22)	18747.724132 MPa
Young's Modulus (E33)	17118.481941 MPa
Poisson's Ratio (NUij)	
Poisson's Ratio (NU12)	0.1481333456
Poisson's Ratio (NU23)	0.1587160485
Poisson's Ratio (NU13)	0.1690974090
Shear Modulus (Gij)	
Shear Modulus (G12)	1941.6160701 MPa
Shear Modulus (G13)	1950.2275087 MPa
Shear Modulus (G23)	3780.7782295 MPa

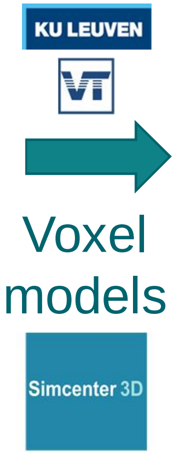
 in collaboration with KU LEUVEN and with the financial support of VLAIO AGENTSCHAP INNOVEREN & ONDERNEMEN via the Innovation Mandate – Virtual-CT (HBC.2017.0189)

Example for mechanical properties

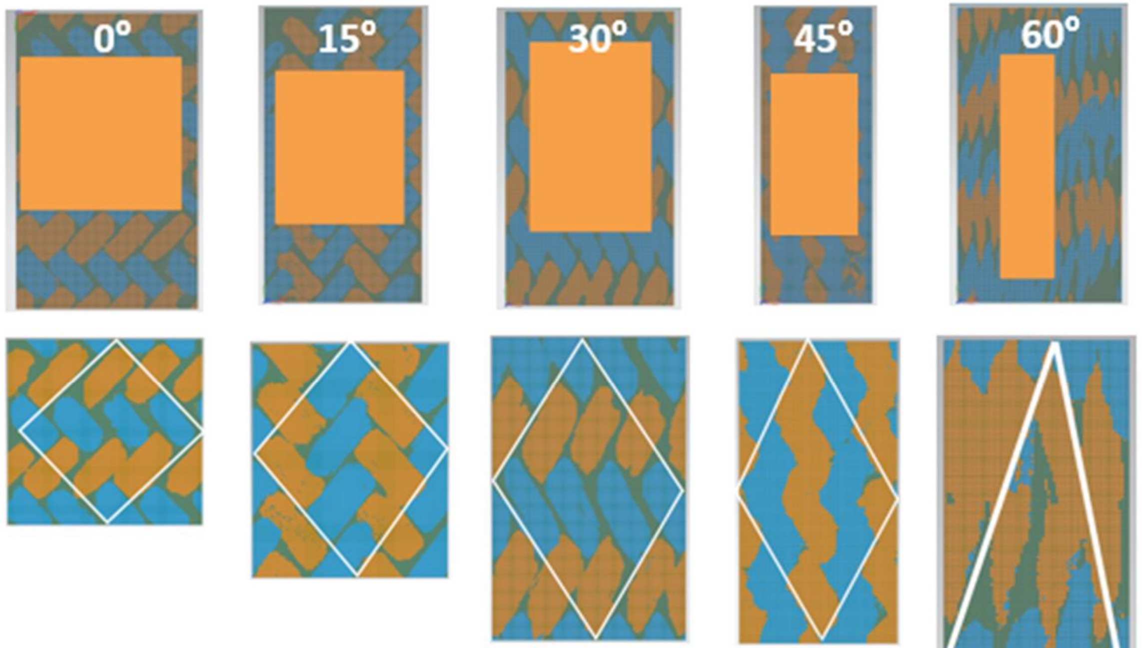
Homogenization for stiffness of sheared organo sheet laminates

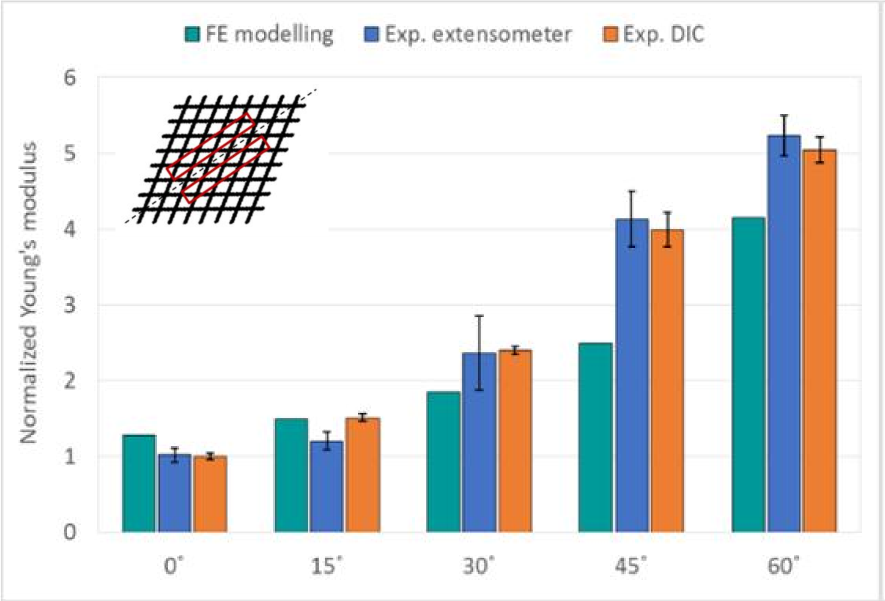


glass roving / PA6

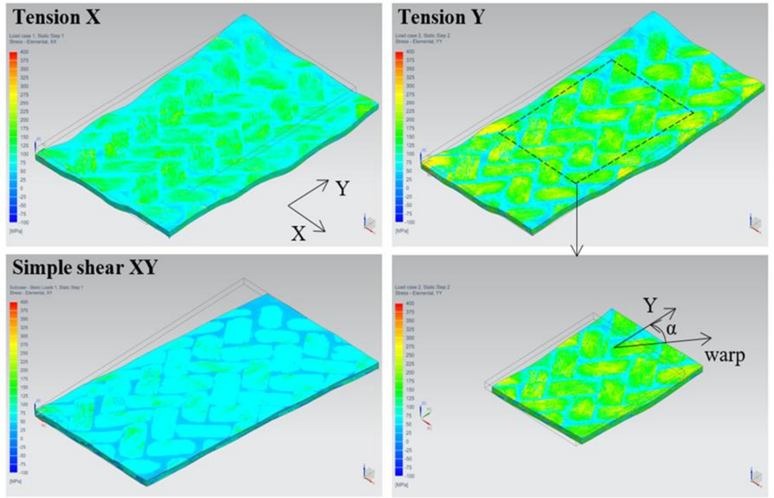


Voxel models





Unit cell homogenization



Automatic 2D PBC usage

Shishkina O., Matveeva A. et al. X-Ray computed tomography-based FE-homogenization of sheared organo sheets, ECCM-18, Athens, Greece, 24-28th June 2018

Example for flow properties

Saturated permeability as input for infusion simulation

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Siemens Simcenter 3D Flow Solver solves Navier-Stokes' equation to predict the liquid resin flow through a system of channels inside the reinforcement. The resulting flow velocity is used to calculate the permeability values, K [m^2], of the reinforcement in the axes of orthotropy.

Composite geometry

- *Idealized* via a geometry generator (WiseTex, TexGen)
- *Realistic* via micro-CT (VoxTex)

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→

Model set-up

- Flow driven by pressure difference
- PBC or symmetry or slip wall
- Flow blockage in yarns (intra-yarn permeability)

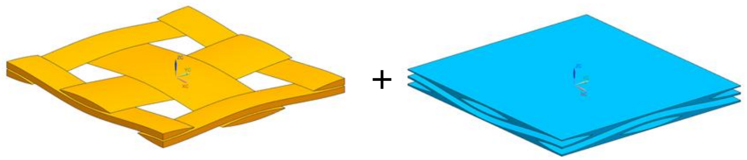
→

Solution

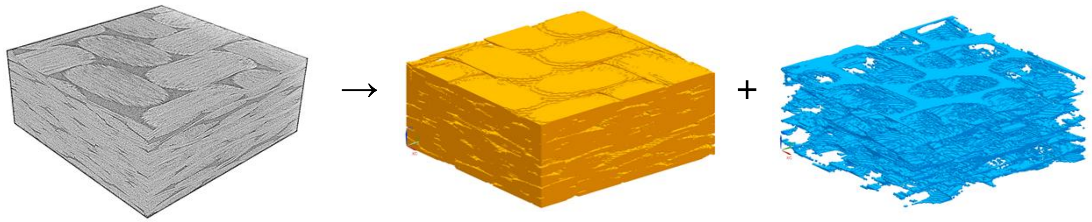
- Velocity field and volume flow rate
- Pressure distribution

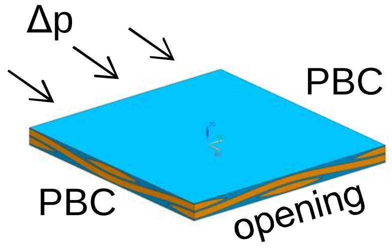
Permeability calculation

Idealized geometry – Plain weave – 1 ply



Realistic geometry – Twill – 4 plies

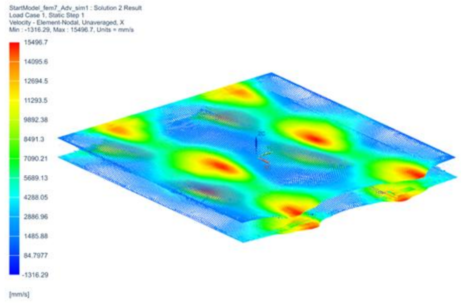


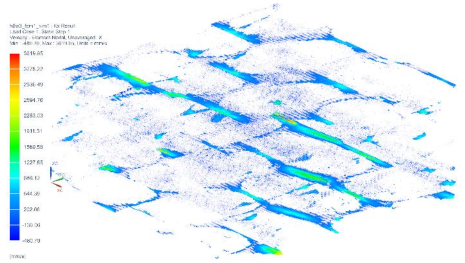


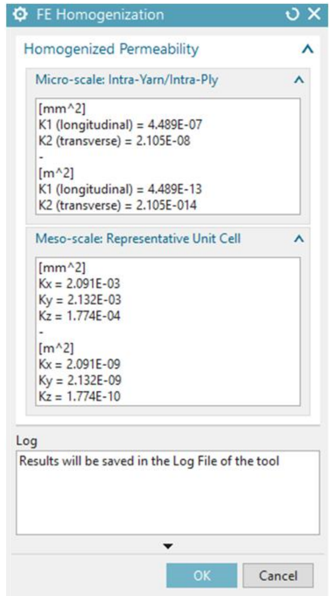
Intra-yarn permeability
(Gebart 1992)

$$K_{\parallel} = \frac{8R^2}{c}\frac{(1-V_f)^3}{V_f^2}$$

$$K_{\perp} = C_1\left(\sqrt{\frac{V_{f\max}}{V_f}}-1\right)^{5/2}R^2$$







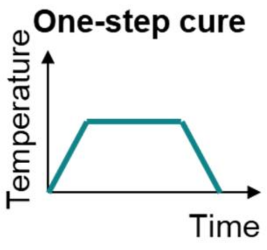
Example for material thermo-mechanical assessment

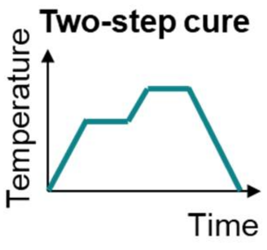
Curing-induced residual stress on micro-scale

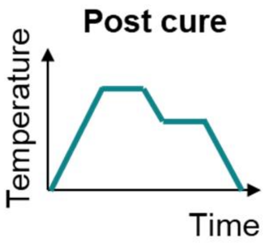
Siemens Simcenter 3D Samcef Solver solves *thermal problem* to assess the degree of cure and glass transition temperature of the curing resin and *mechanical problem* to calculate the induced residual stress, which later can be mapped on the structure for performance evaluation.

- *Estimate the effect of*
  - *curing cycle parameters (T°, heating/ cooling rate, type),*
  - *matrix relaxation (visco-elastic behavior),*
  - *fiber volume fraction (FVF)*

  on curing-induced residual stress.
- *Optimize curing cycle to minimize residual stress.*

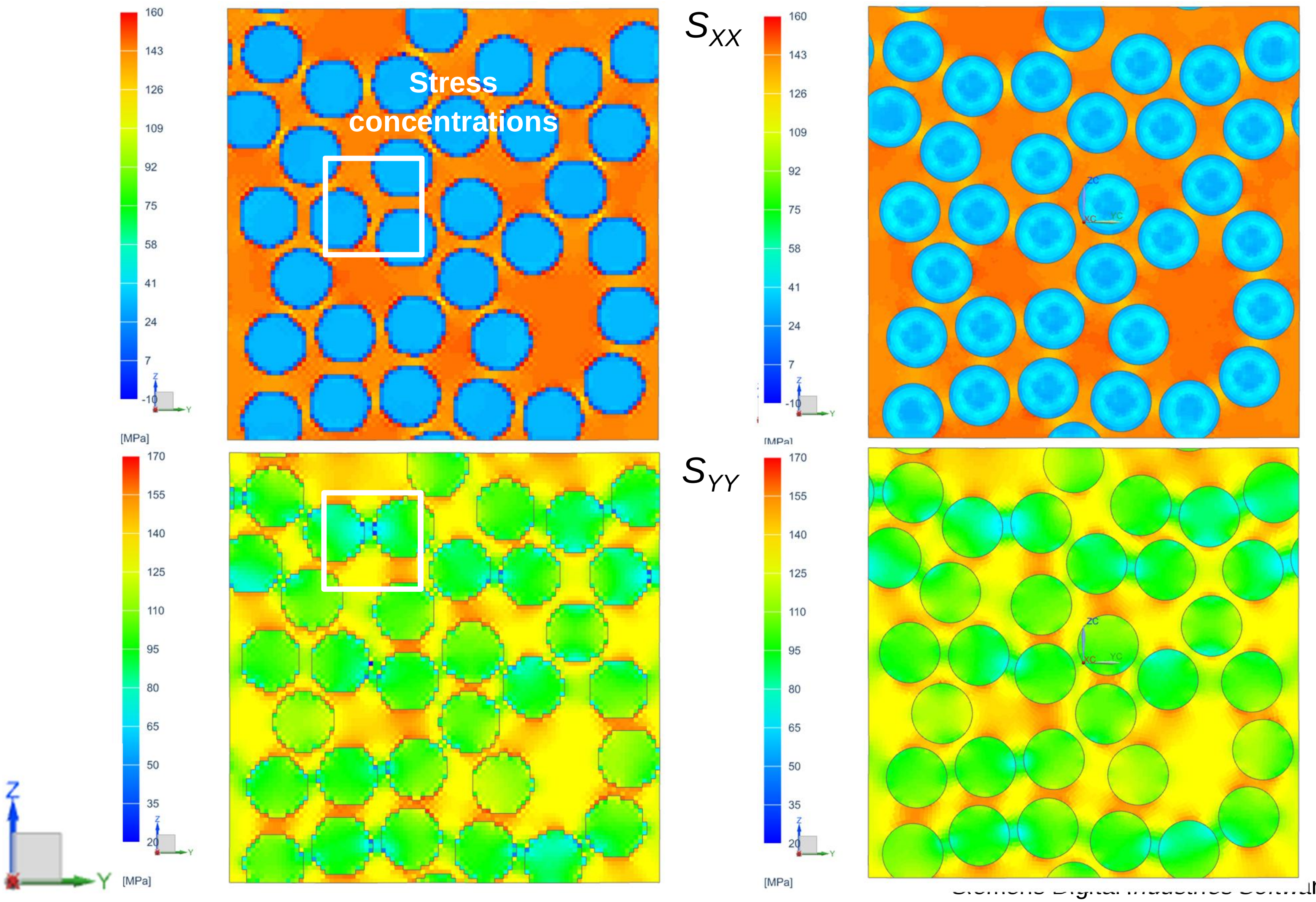






Unit cell with randomly arranged fibers

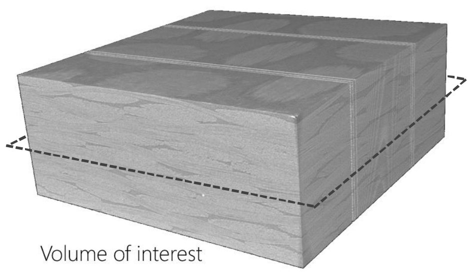
carbon fiber-reinforced epoxy, volume fraction of 50%

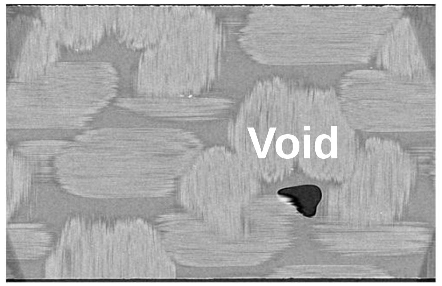


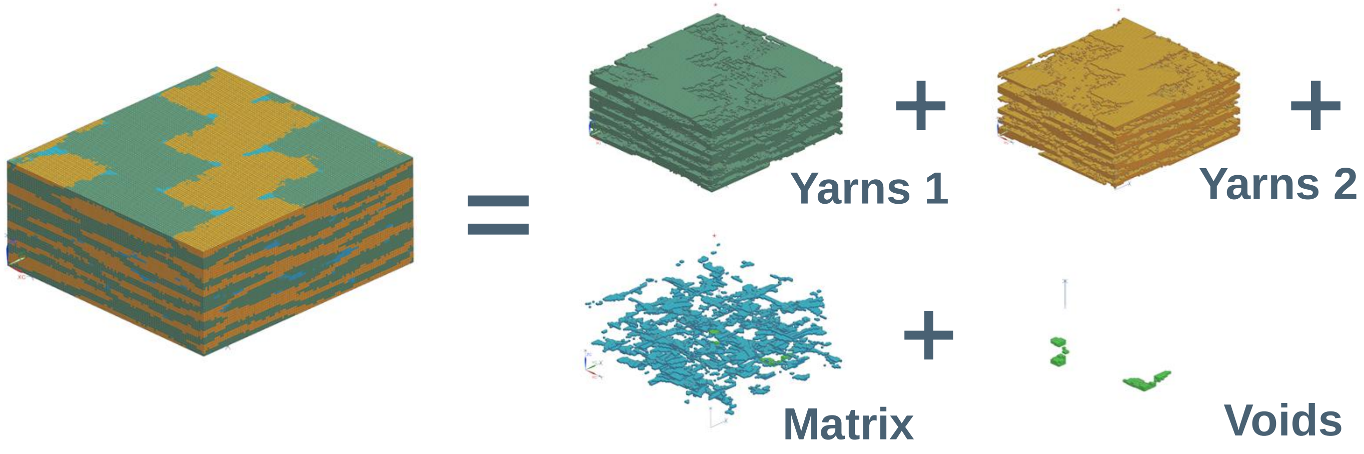
Voxel-based geometry representation
Summary

Advantages

- **Realistic composite geometry** can be introduced in simulations including *geometrical variability and possible defects* due to the manufacturing process

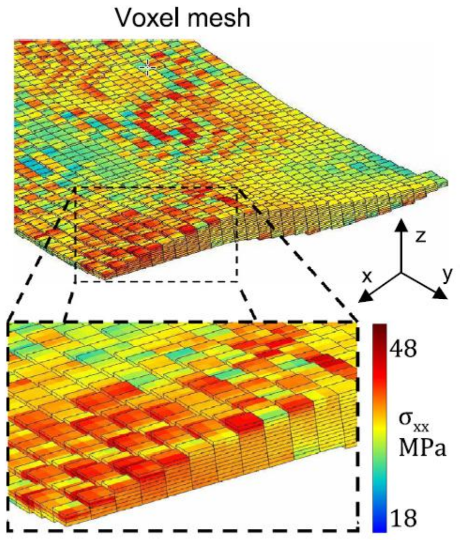


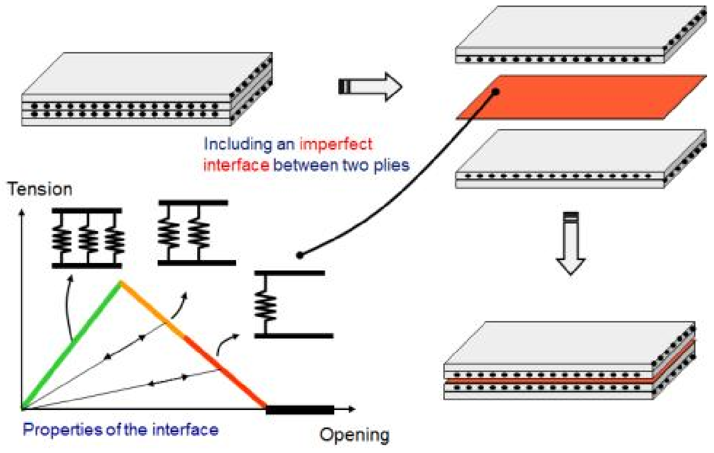




Drawbacks

- **Stress concentrations** due to the step-like shape of voxels induce significant differences for the first damage prediction
- **Absence of a smooth matrix-yarn interface** for modeling inter-yarn damage (decohesion)





A. Doitrand et al. / Composites: Part A 73 (2015) 143–154

Voxel model to a parametric CAD model
Simcenter Convergent Modeling Technology

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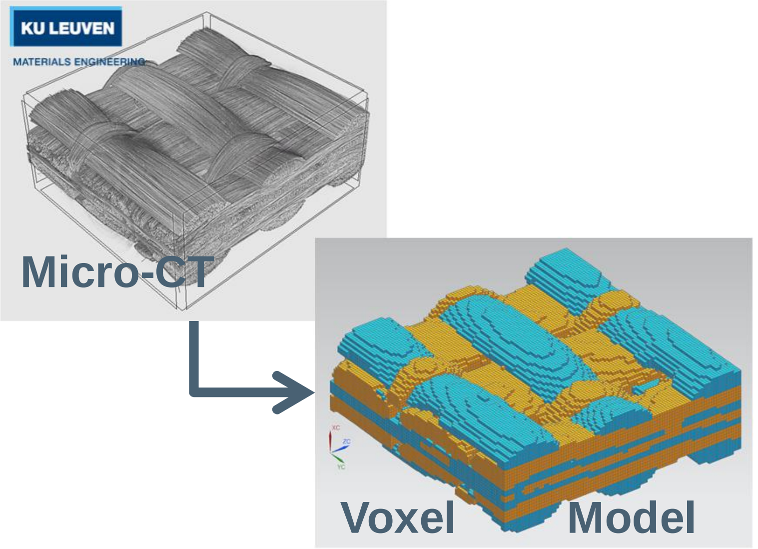
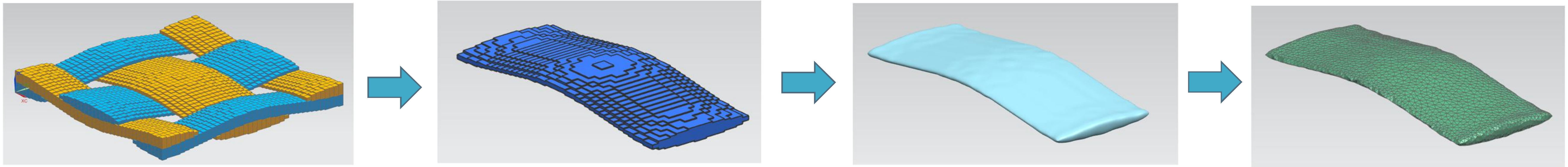
A way to overcome drawbacks:

ü *Micro-CT and image analysis techniques* produce digital (voxel-based or faceted) data of the [composite] geometry

ü From these models, *construct surfaces using Simcenter Convergent Modeling technology,* which match the 3D scan data and exploit the new realistic geometry to achieve higher accuracy of the modeling prediction



***Simcenter Convergent Modeling** allows effectively use facet, surface and solid geometry in a single model without a need for any conversion (= time savings) while maintaining the feature history*



Voxel model → Convergent body → Smoothed CAD model → Re-meshing

Simcenter Convergent Modeling Technology

Example: curing of the unit cell with randomly arranged fibers

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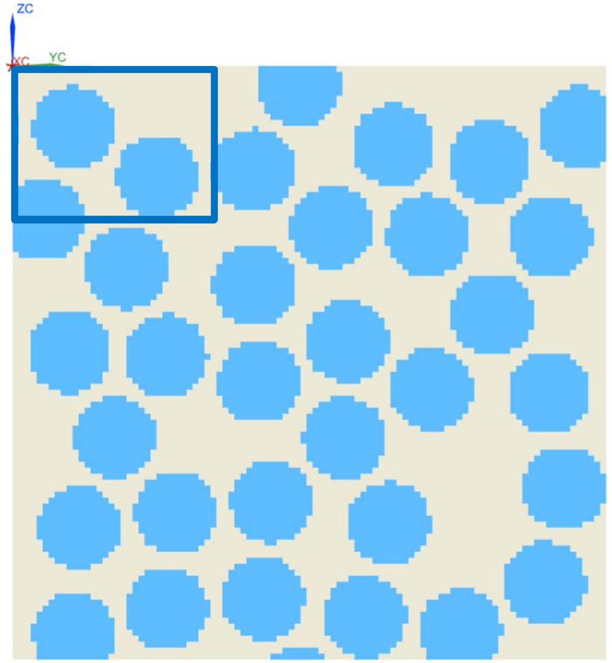
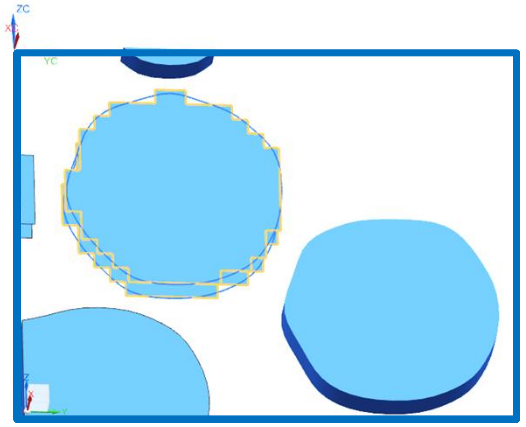
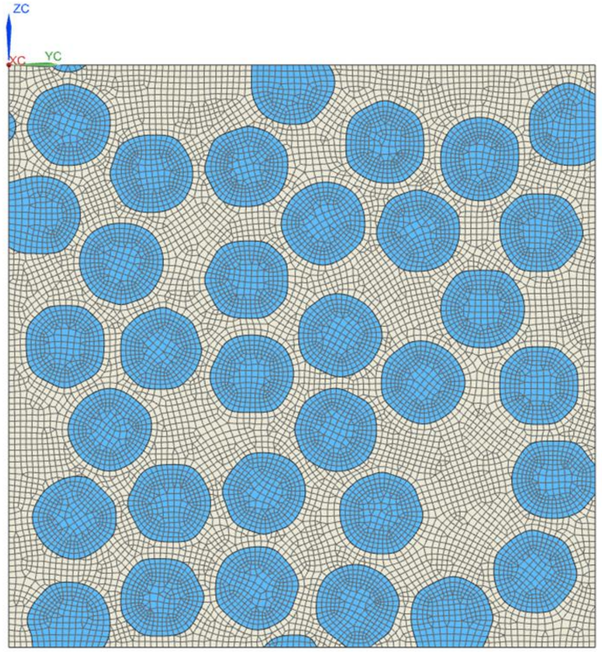


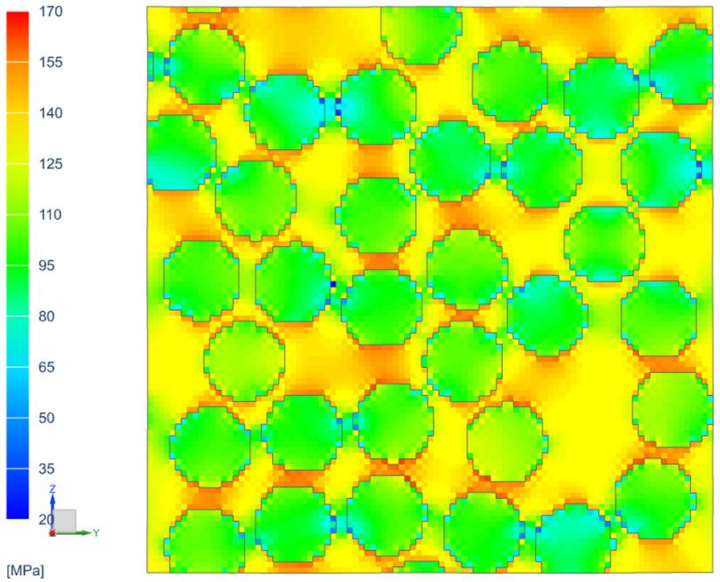
Voxel model

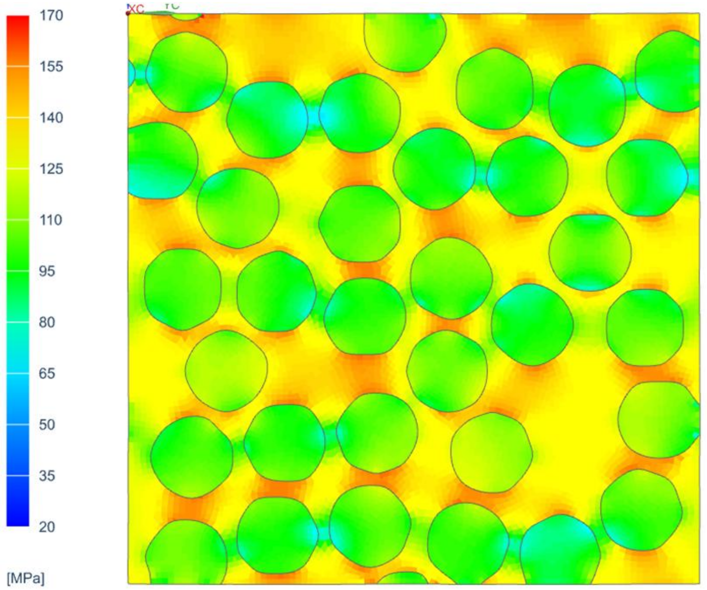


Smoothening the "staircase": the largest surface contained in the voxel geometry



CAD model including feature history





Curing-induced residual stress (S_{YY})

A new challenge related to the "weak" periodicity of realistic geometries

Image-based modeling of other materials
Application to additive manufacturing

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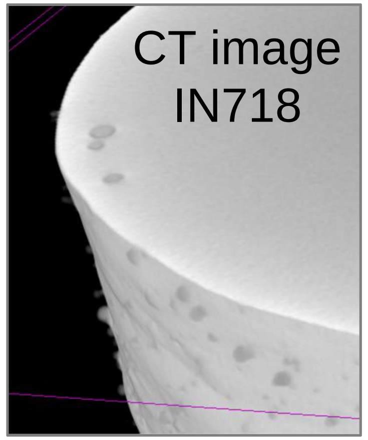
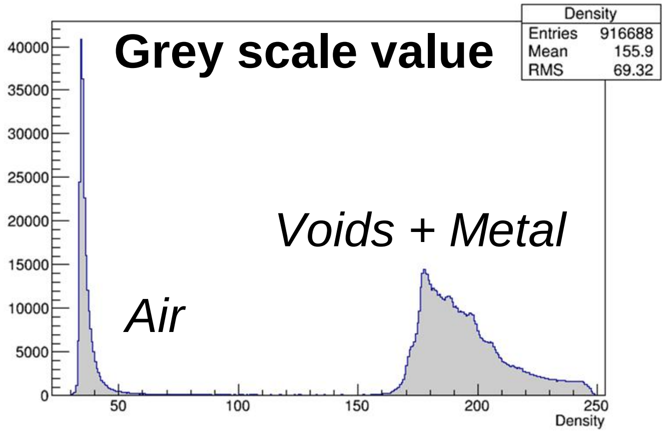
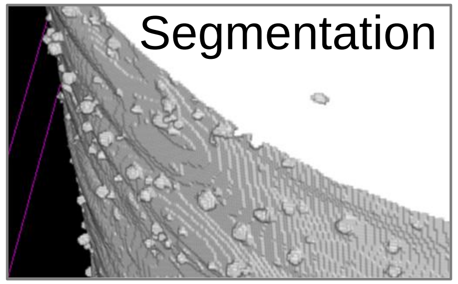
VirtualCT for VMC ToolKit *is a universal tool which allows import of segmented images from different structures, e.g. 3D-printed metal samples*

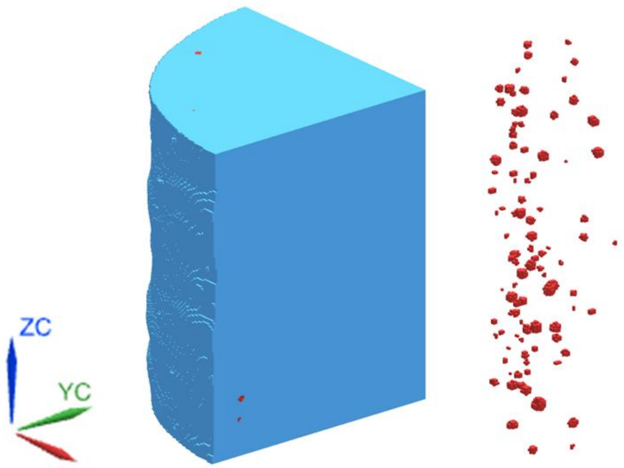
Challenges remain the same:

- **Image acquisition and segmentation:** preserve surface roughness and include voids. In the example, their grey scale value is very similar
- **Resolution limitations:** ratio between the studied feature and voxel size. More features consideration leads to larger FE models (~ millions of elements)
- **Voxel-based geometry representation** leading to artificial stress concentrations. Extra-step is required to produce CAD models









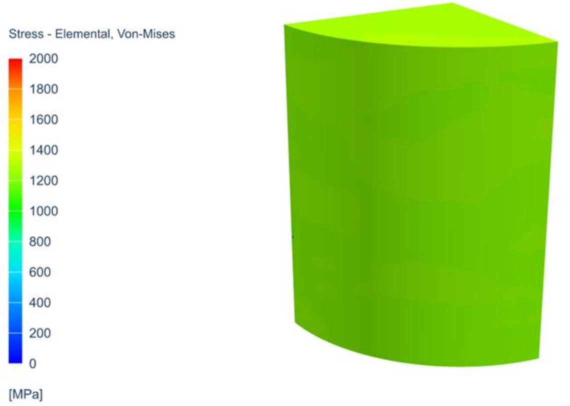
Sample Voids

Simcenter 3D

Structural simulation

Axial tension (ZC)

Von-Mises Stress



in collaboration with Siemens Corporate Technology, Berlin

Final conclusions

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More reality (details) in the modeled geometry leads to higher accuracy of the modeling prediction

- *Micro-CT image-based modeling allows considering "as-manufactured" [composite] material geometry which includes geometrical variability and possible defects*

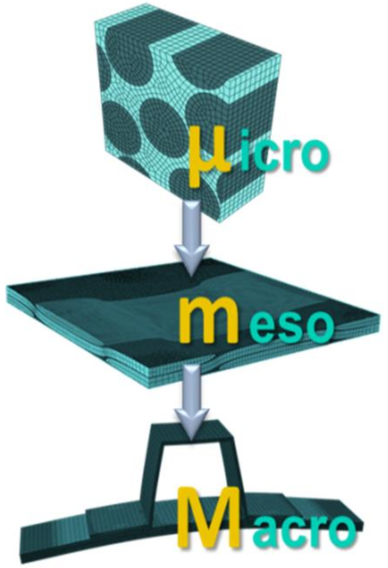
Challenges

- *Relatively slow: time-demanding image acquisition and processing*
- *Resolution limitations: ratio between the studied feature and voxel size*
- *Smoothening of step-like shape of voxels to eliminate unphysical stress concentrations - solved*
- *"Weak" periodicity of realistic geometries leads to stress concentrations at the UC boundaries*

Simcenter 3D

VMC ToolKit

to accelerate material engineering by virtual testing



Acknowledgements

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The authors gratefully acknowledge **SIM (Strategic Initiative Materials in Flanders)** and **VLAIO (the Agency Flanders Innovation & Entrepreneurship**) for their support of the ICON project M3Strength (Grant no.140158) which fits in the research program **MacroModelMat (M3)** coordinated by Siemens (Siemens PLM Software, Belgium).

O. Shishkina thanks VLAIO for financing her work in the framework of the Innovation Mandate Project "**Virtual-CT**: Micro-CT-based Model Generation Engine for Virtual Material Characterization" (Grant no. HBC.2017.0189).

S.V. Lomov holds **Toray Chair** for Composite Materials at KU Leuven, the support from which is also acknowledged. CT images were made at the **Department of Materials Engineering** (MTM) in the **X-ray CT center of the KU Leuven** (Belgium) and by **TESCAN XRE** (Belgium) at their facilities.

M^3 Macro Model Mat

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Thank you.

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