Schnelle Berechnung der effektiven mechanischen Eigenschaften von Verbundwerkstoffen

Endlos- und Kurzfaserverbunde

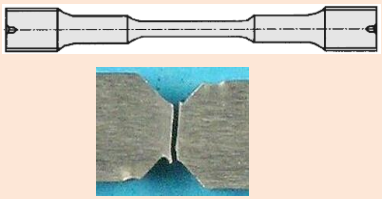
Georg Falkinger

4a Technologietag Schladming
28.02.2013

Fraunhofer
IWM

Damage Concept: multi step proof of crashworthiness

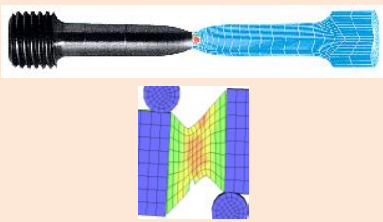
Material

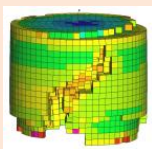


Tension-, compression-, shear-Tests
static, dynamic

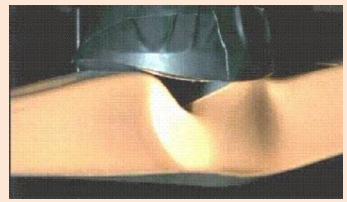
Material models

Simulation of specimen tests





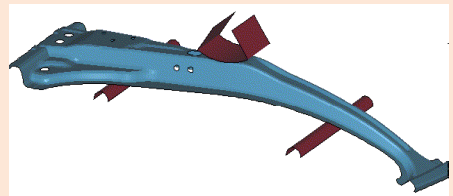
Component



Substructure crash test
(e.g.: B column)

Structural modeling

Simulation of component tests



Vehicle

Full scale test

Crashworthiness prediction

Simulation of Full-Scale Tests

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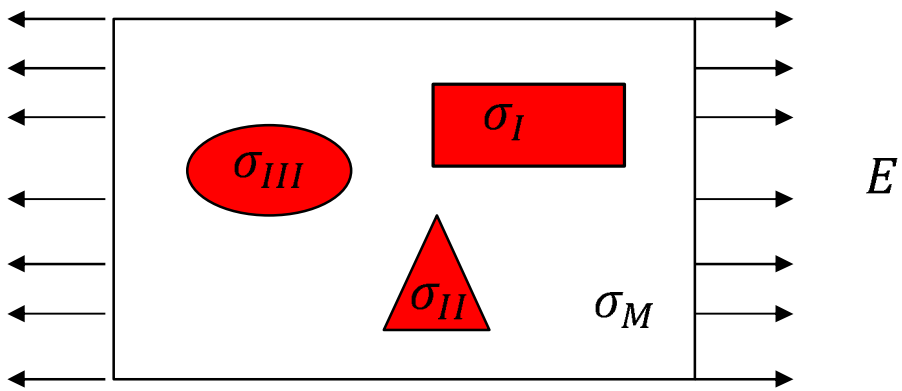
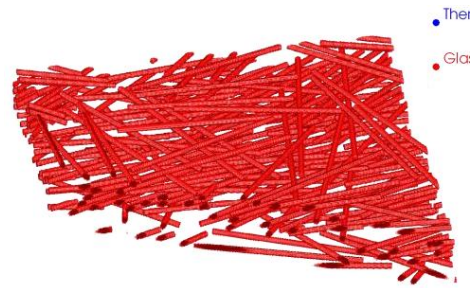
Effektive mechanische Eigenschaften
Methcdische Ansätze

Effektive Spannung: $\Sigma(E)$





Finite-Elemente
- Lokale Felder
- Große Deformationen
- $Konvergenz \sim N^2$

Mean-Field Methoden
- Semi-analytische Lösungen
- Mit gemittelten Größen
- zB Mori-Tanaka

Fraunhofer IWM

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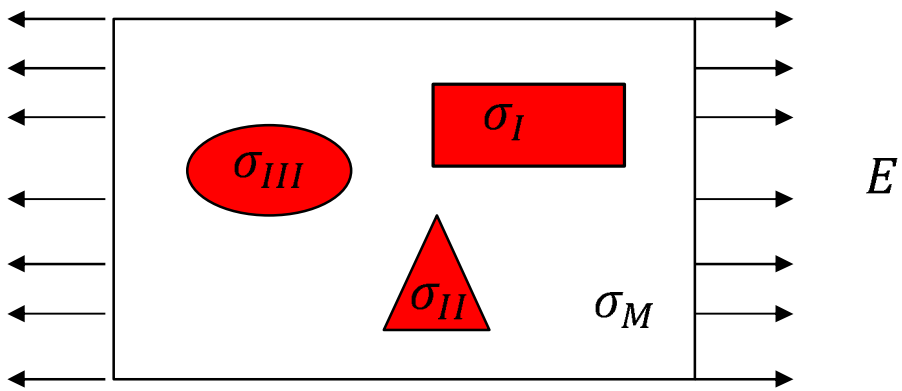

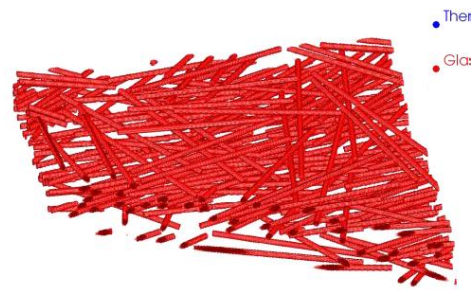

Finite-Elemente
- Lokale Felder
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Voxelbasiert/FFT
- Lokale Felder
- Grosse Strukturen
- Kleine Deformationen
- $Konvergenz \sim N \ln N$

Mean-Field Methoden
- Semi-analytische Lösungen
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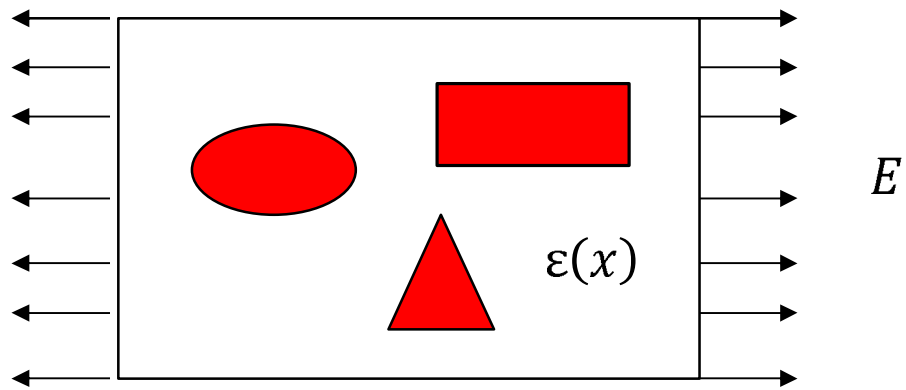
- zB Mori-Tanaka

Fraunhofer IWM

Homogenisierung von Verbundwerkstoffen
„FFT-Methode

Mechanisches Gleichgewicht	$div\ \sigma = 0$	Gesucht $\varepsilon(x) = ?$
Materialgesetz	$\sigma(\varepsilon)$	
Randbedingungen	Periodische Randbedingungen	



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Homogenisierung von Verbundwerkstoffen
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$$\sigma = \sigma(\varepsilon) = C^0\varepsilon + (\sigma(\varepsilon) - C^0\varepsilon) \equiv C^0\varepsilon + \tau$$

Homogenes Medium mit Steifigkeit C^0 und „Störung“ τ

Fraunhofer IWM

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$$\tau = C^0\varepsilon - \sigma(\varepsilon)$$

$$\boxed{\varepsilon(x) = E - [G^0 \star \tau\,](x)}$$

Lösung mit Hilfe der Green’s Funktion G^0

Lippmann-Schwinger Gleichung

Moulinec&Suquet 1998; Brisard&Dormieux 2010;

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Lösung mit Hilfe der Green’s Funktion G^0

Lippmann-Schwinger Gleichung

Solver mit GUI von Fraunhofer-Institut für Techno- und Wirtschaftsmathematik (ITWM) Kaiserlautern, Dr. M. Kabel

FeelMath

Moulinec&Suquet 1998; Brisard&Dormieux 2010;

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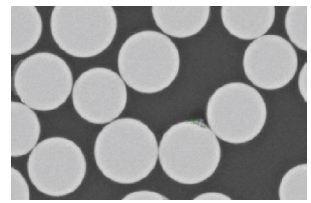
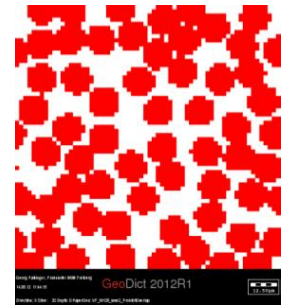
Überblick Voxelbasierte FFT-Methode





- Diskretisiertes Voxel-Gitter
- Nur „Bulky“ Strukuren
- Beliebiges nicht-lineares Materialverhalten
- Immer periodische Randbedingungen
- Kleine Deformationen (kein Unterschied Wahre Dehnung-Technische Dehnung)
- Konvergenzrate geht mit Steifigkeitskontrast runter (Extremfall Poren)
- Beliebige Lastpfade (zyklisch, etc)
- Keine Vernetzung notwendig, trotzdem hohe Anforderungen an Strukturgenerierung
- Kann direkt auf Tomographiebild rechnen
- Niedriger Arbeitsspeicher, schnelle Rechenzeit
- Keine genaue Abbildung von Phasengrenzen (interfaces)

Homogenisierung der elastischen Eigenschaften (*Nguyen N. et al.* 2008)

- Eshelby-Mori-Tanaka Schema für parallel orientierte Fasern

  M…..Matrix

  F……Faser

  S……Eshelby-Tensor
- Mittelung über Faserlängenverteilung p(l)
- Der Steifigkeitstensor des Faserverbunds wird aus den Orientierungstensoren **a** und den Invarianten b_i des Steifigkeitstensors für parallel liegenden Fasern gebildet.
- Alternative Ansätze: Selbstkonsistenz-Bedingung, Variationsmethoden

$$\mathbf{A}_{\mathrm{F(MT)}} = \left[\mathbf{1} + c_{\mathrm{M}}\mathbf{S} : \mathbf{C}_{\mathrm{M}}^{-1} : (\mathbf{C}_{\mathrm{I}} - \mathbf{C}_{\mathrm{M}})\right]^{-1}$$

$$\mathbf{C}^{*}_{\mathrm{(MT)}} = \mathbf{C}_{\mathrm{M}} + c_{\mathrm{F}}(\mathbf{C}_{\mathrm{F}} - \mathbf{C}_{\mathrm{M}}) : \mathbf{A}_{\mathrm{F(MT)}}$$

$$\mathbf{C} = \frac{\int \mathbf{C}^{*}_{\mathrm{(MT)}}(l)\,\mathrm{p}(l)\,\mathrm{d}l}{\int \mathrm{p}(l)\,\mathrm{d}l}$$

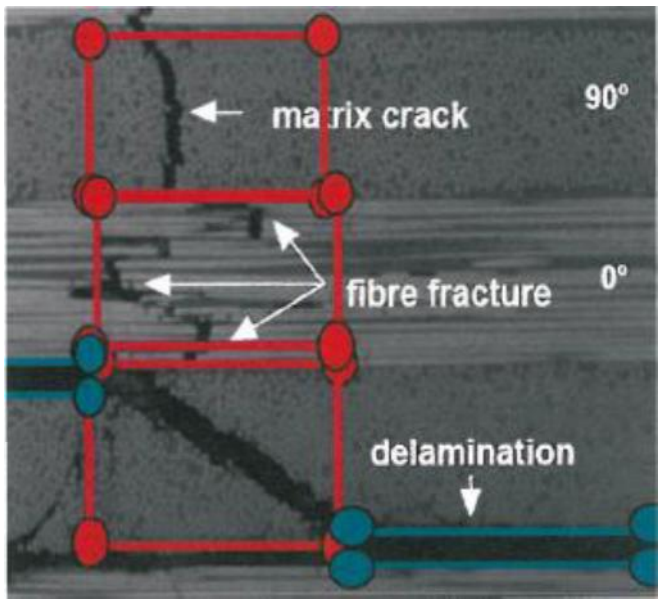
$$\mathbf{C}_{\mathrm{(LFT)}} = b_1\mathbf{a}_{ijkl} + b_2(\mathbf{a}_{ij}\boldsymbol{\delta}_{kl} + \mathbf{a}_{kl}\boldsymbol{\delta}_{ij}) + \\ + b_3(\mathbf{a}_{ik}\boldsymbol{\delta}_{jl} + \mathbf{a}_{il}\boldsymbol{\delta}_{jk} + \mathbf{a}_{jl}\boldsymbol{\delta}_{ik} + \mathbf{a}_{jk}\boldsymbol{\delta}_{il}) + \\ + b_4\boldsymbol{\delta}_{ij}\boldsymbol{\delta}_{kl} + b_5(\boldsymbol{\delta}_{ik}\boldsymbol{\delta}_{jl} + \boldsymbol{\delta}_{il}\boldsymbol{\delta}_{jk})$$

Results

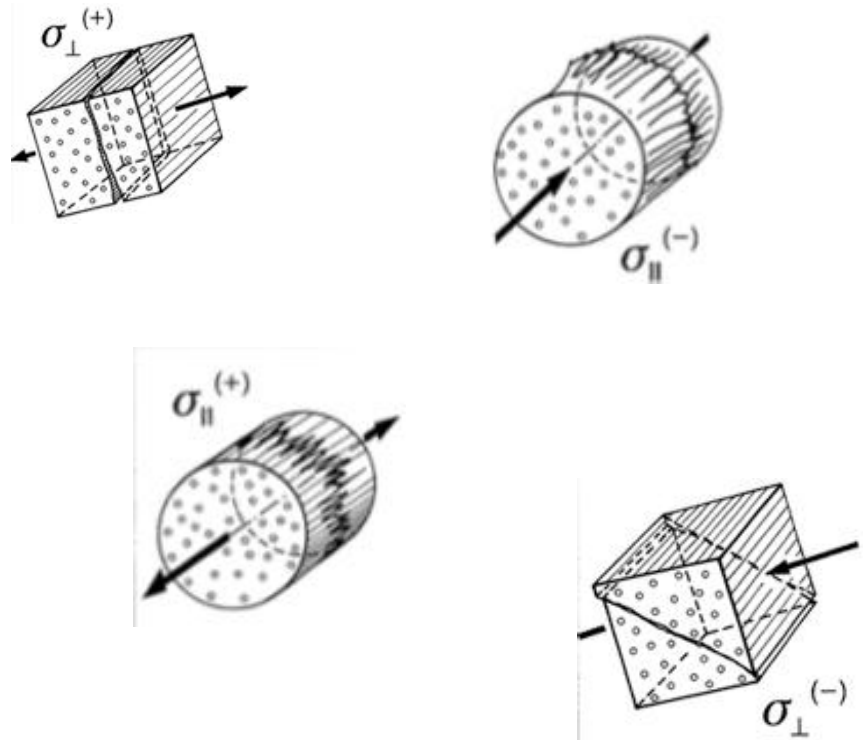
- (UD) Uni-directional layers and laminates
  - Comparison with FEM (Abaqus)
  - UD-layers and laminates
  - Non-linear behaviour
- Short-Fibre reinforced Polymers
  - Analytical Model
  - Fibre-Volume
  - Fibre-Length
  - Fibre –Orientation
  - Non-linear behaviour
- Outlook

UD-Layers and Laminates

Challenge: Predit mechanical properties and Failure

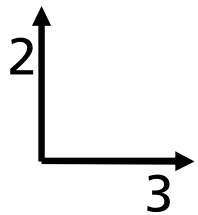


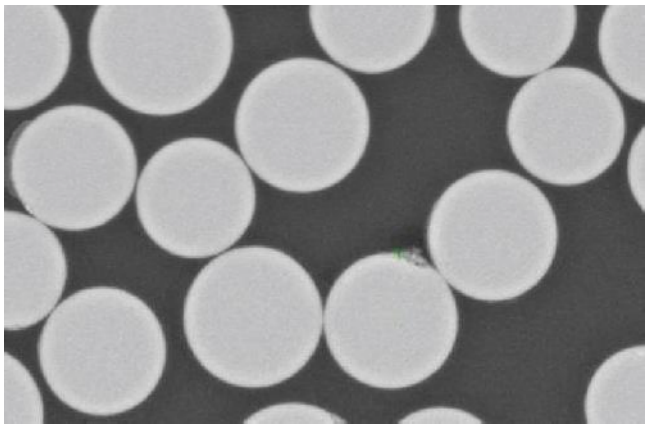
Source: dynamore GmbH



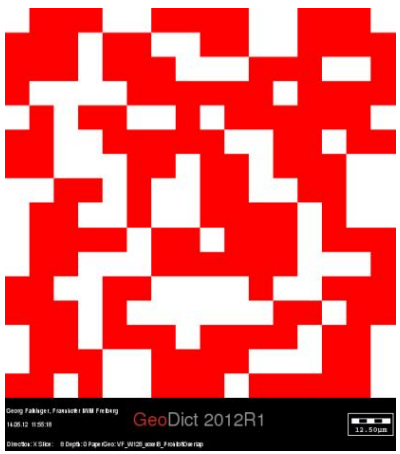
UD-Layers: Glass-fibres in epoxy resin
Calculation of effective elastic properties

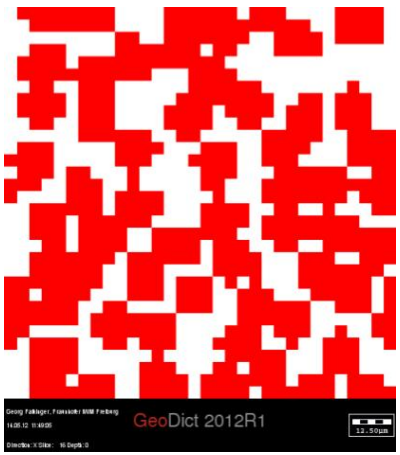
- Glass Fibre: E=73 Gpa, v=0.18
- Epoxy Resin: E=4 Gpa, v=0.22
- Volume content: 60%
- Structure generation with GeoDict

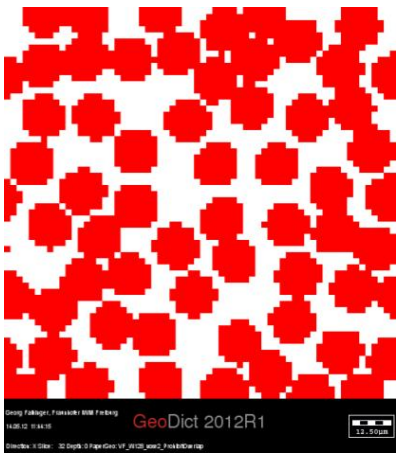


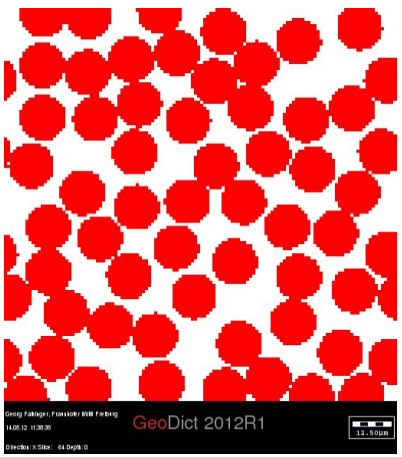


Source: www.compositesworld.de









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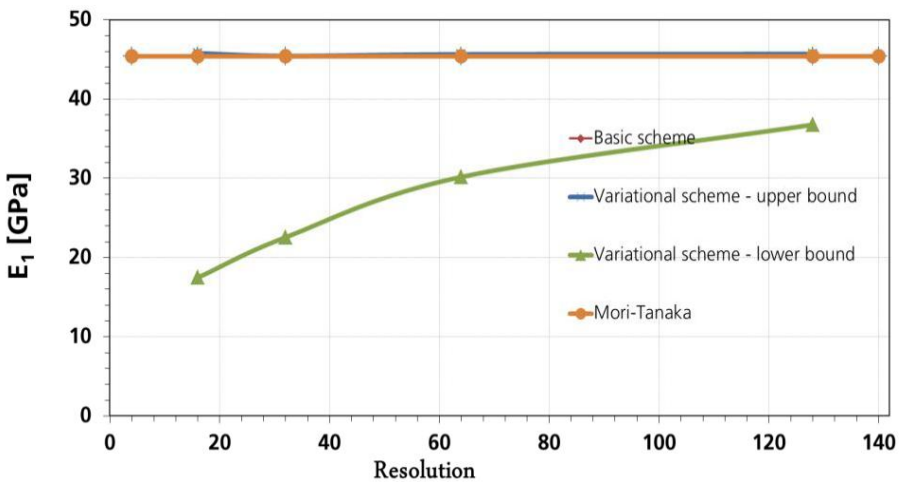
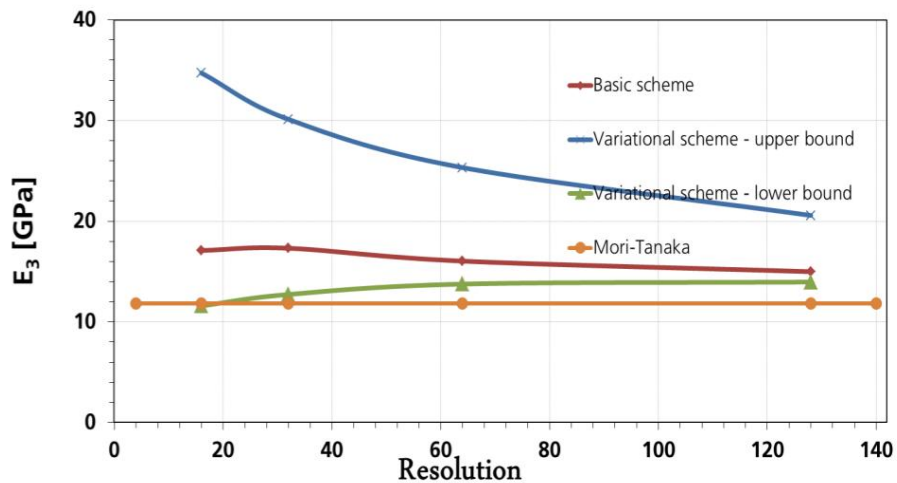
UD-Layers: Glass-fibres in epoxy resin

Calculation of effective elastic properties

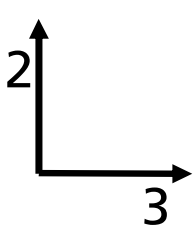
FeelMath

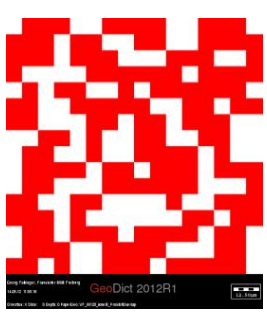


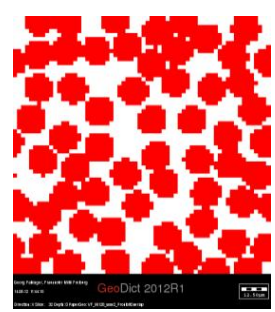


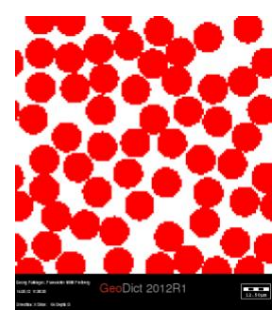
E in fibre direction 47 GPa

E perpendicular to fibre direction 16 GPa









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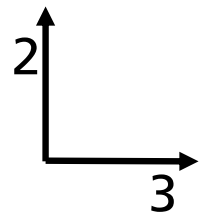
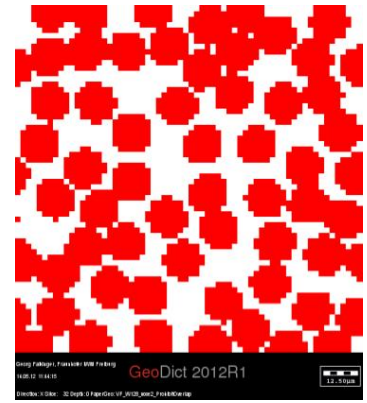
UD-Layers: Glass-fibres in epoxy resin

Calculation of effective elastic properties

FeelMath

- 64x64x64 Voxel
- 1 Voxel = 2 µm
- Fibre diameter 16 µm





	C1	C2	C12	C44	C66	
Abaqus	47.2	17.6	4.1	8.1	6.1	
FeelMath-Vox	47.2	17.2	4.1	8.1	6.2	

	Memory	CPU-Time
Abaqus	1800 MB	~500s*
FeelMath-Vox	60 MB	~30s

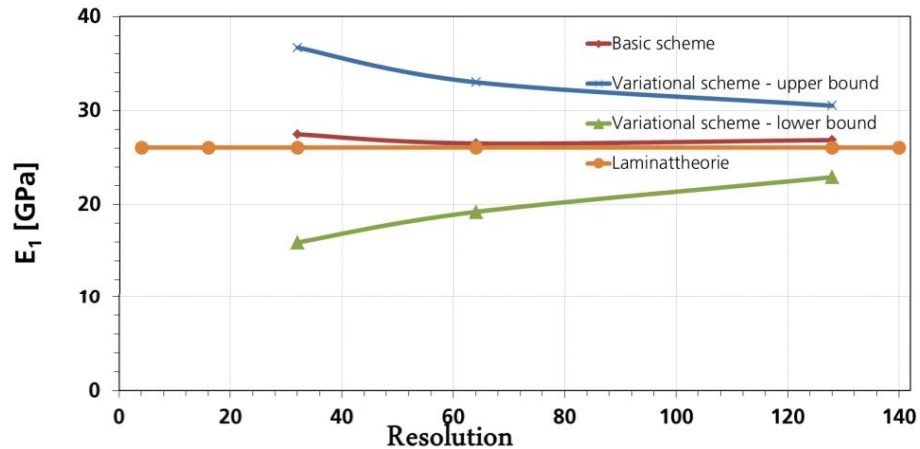
*4 CPUs

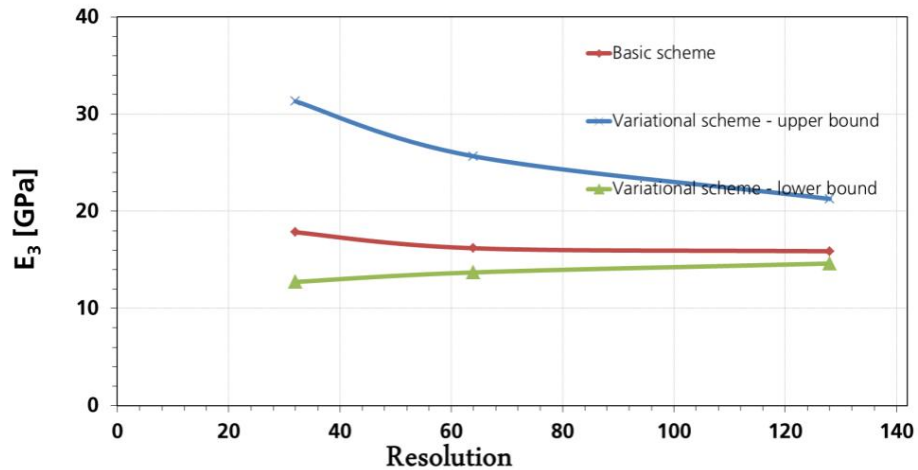
Fraunhofer IWM

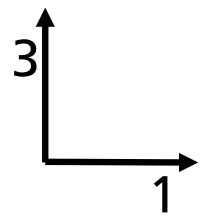
Laminate: Glass-fibres in epoxy resin

Calculation of effective elastic properties

- 64x64x518 Voxel
- 0°/90°/+45°/-45° symmetric Laminate
- Analytical Predictions from Laminate theory
- Realistic dimensions: Laminate Thickness 1 mm







Fraunhofer IWM

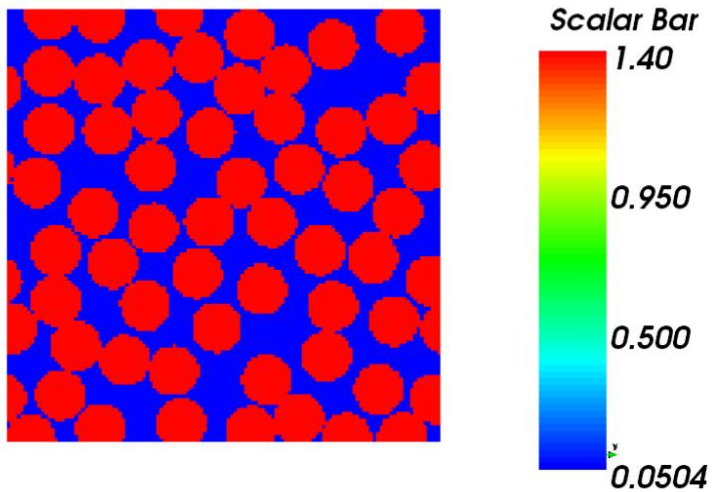
UD-Layers: Glass-fibres in epoxy resin

Perfect Matrix plasticity: Yieldstress 0.05 GPa

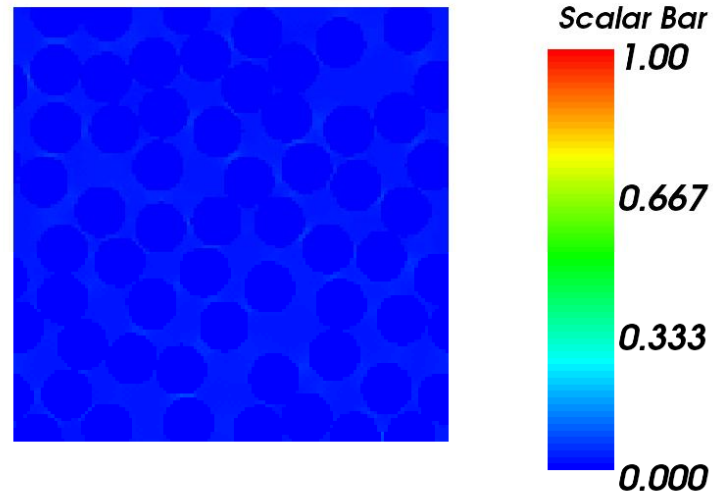
FeelMath

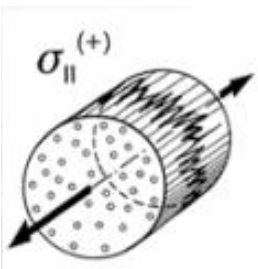
- 128x128x128Voxel
- 1 Voxel = 1 µm
- Fibre diameter 16 µm

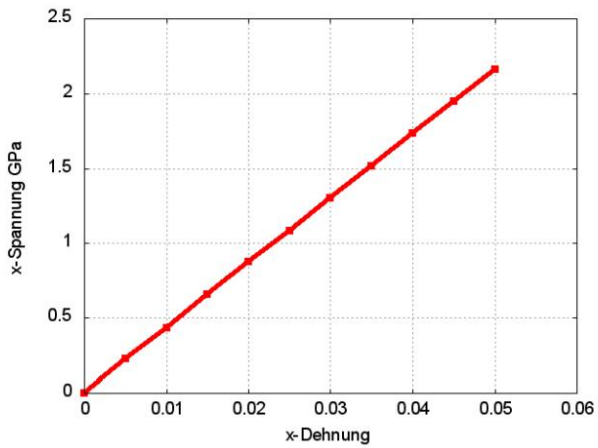
$\sigma M\ GPa$

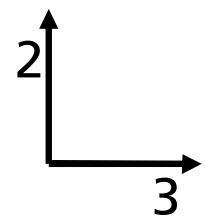


$\varepsilon\ plastisch$







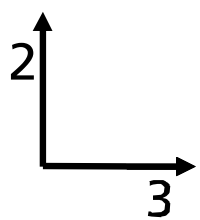


Fraunhofer IWM

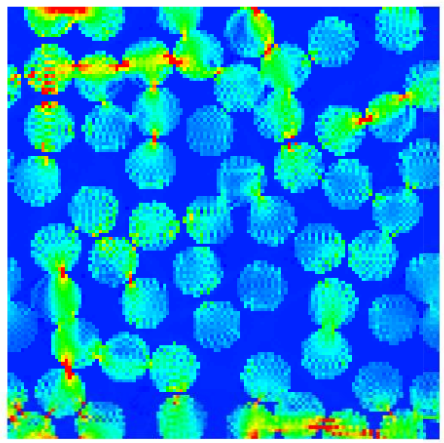
UD-Layers: Glass-fibres in epoxy resin

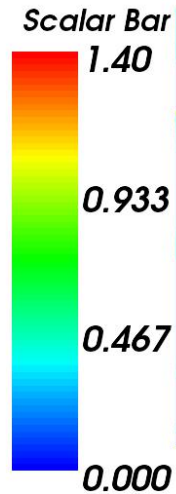
Perfect Matrix plasticity: Yieldstress 0.05 GPa

FeelMath

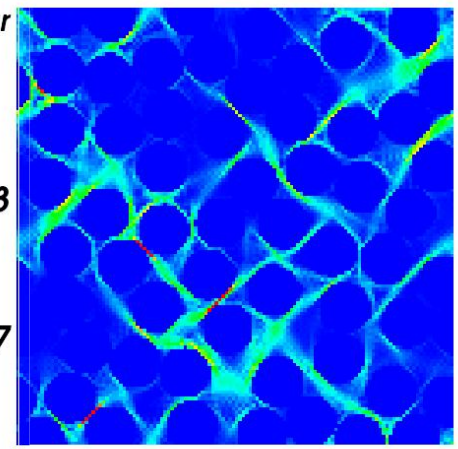


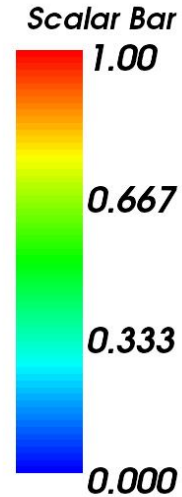
$\sigma M\ GPa$

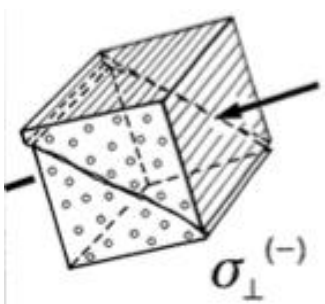


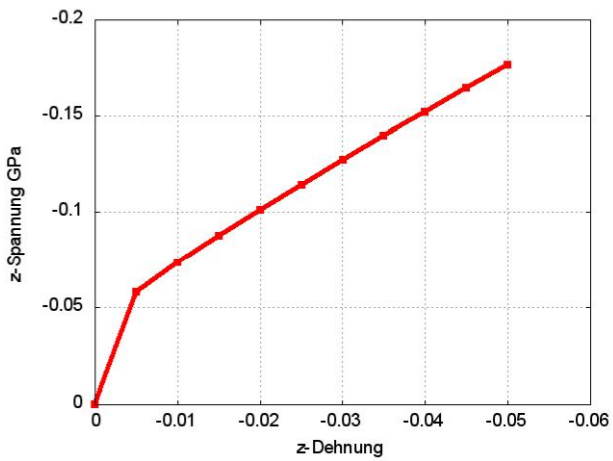


$\varepsilon\ plastisch$





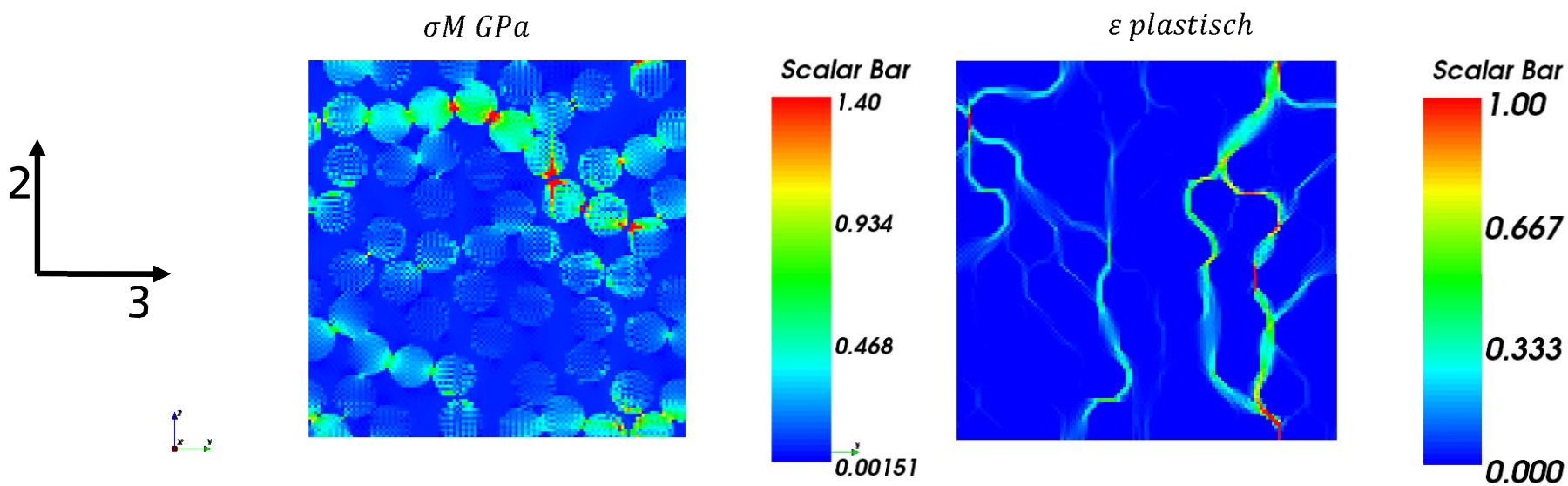


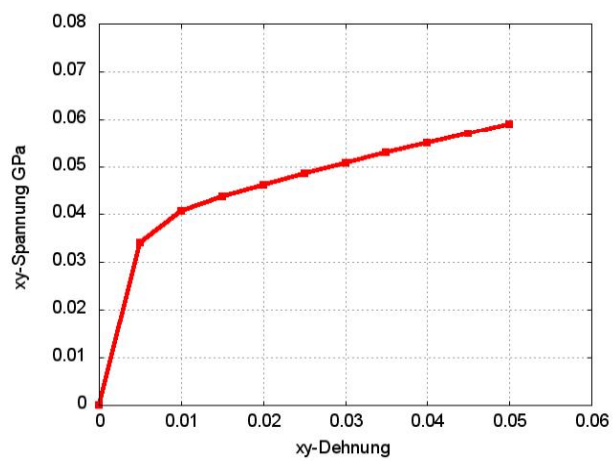


Fraunhofer IWM

UD-Layers: Glass-fibres in epoxy resin

Perfect Matrix plasticity: Yieldstress 0.05 GPa





Fraunhofer IWM

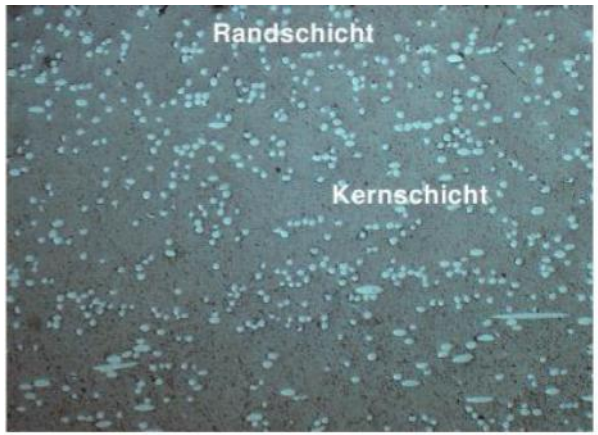
Agenda

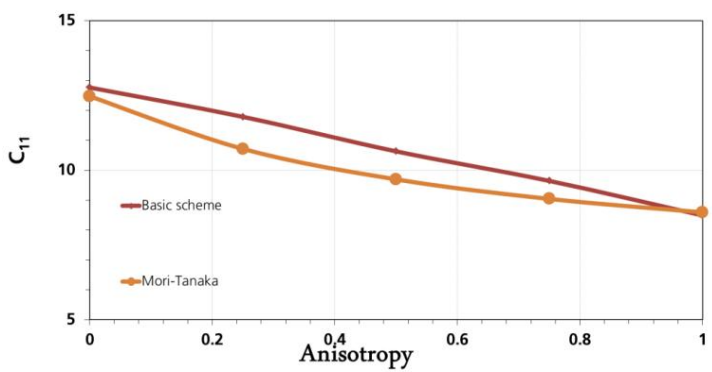
- Motivation
- (UD) Uni-directional layers and laminates
  - Comparison with FEM (Abaqus)
  - UD-layers and laminates
  - Non-linear behaviour
- Short-Fibre reinforced Polymers
  - Analytical Model
  - Fibre - Orientation
  - Fibre - Length
  - Fibre - Volume
  - Non-Linear Behaviour
- Outlook

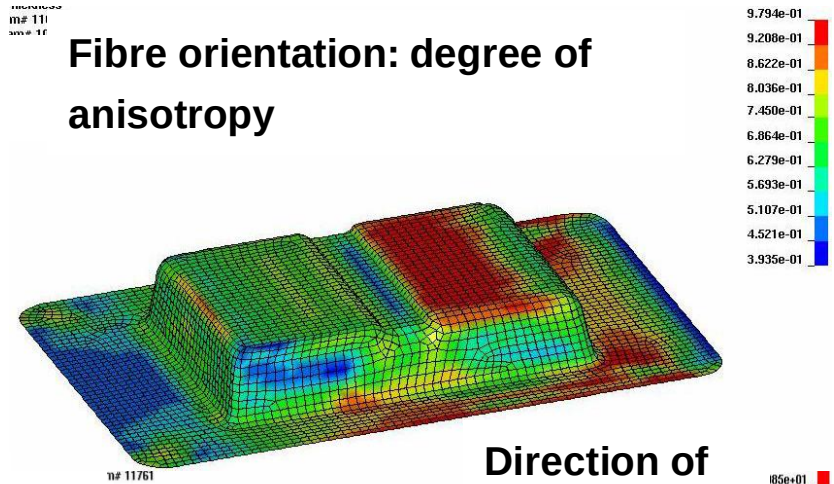
Prozesssimulation langfaserverstärkte Thermoplaste

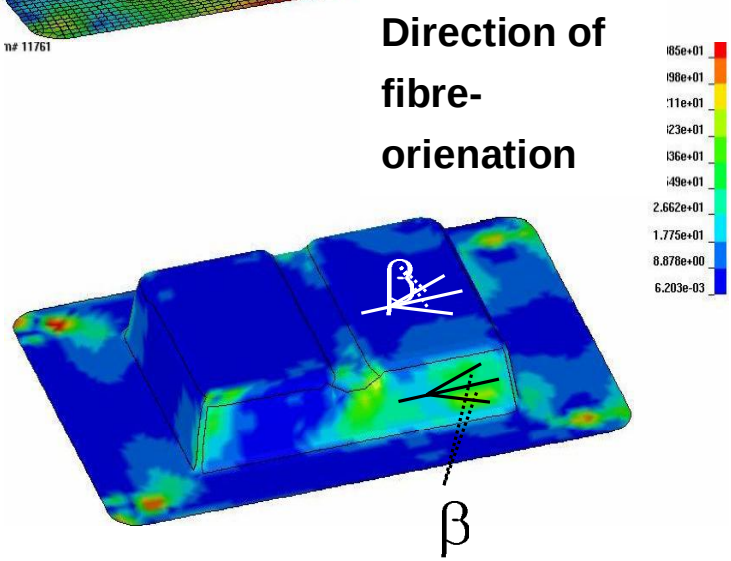
Bestimmung der lokalen Eigenschaften

Numerische Homogenisierung







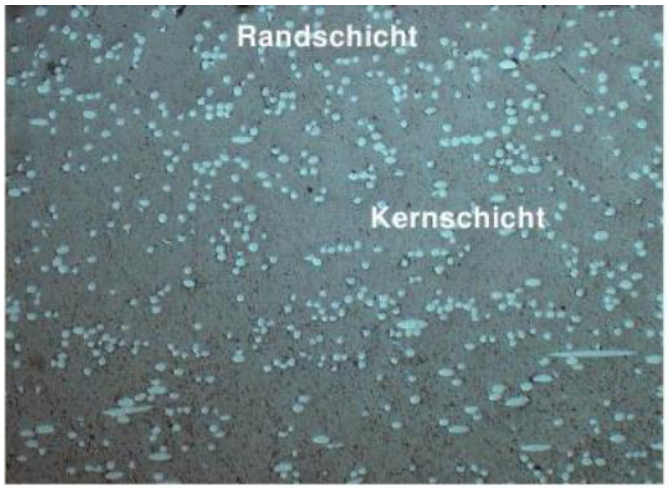


Prozessimulation

Fraunhofer IWM

Short Glass-fibres in thermoplastic matrix
Calculation of effective elastic properties

- Glass Fibre: E=73 Gpa, v=0.18
- Thermoplast Matrix: E=1 Gpa, v=0.38
- Mass content: 20%; Volume fraction 13.8%
- Structure generation with FiberGeo

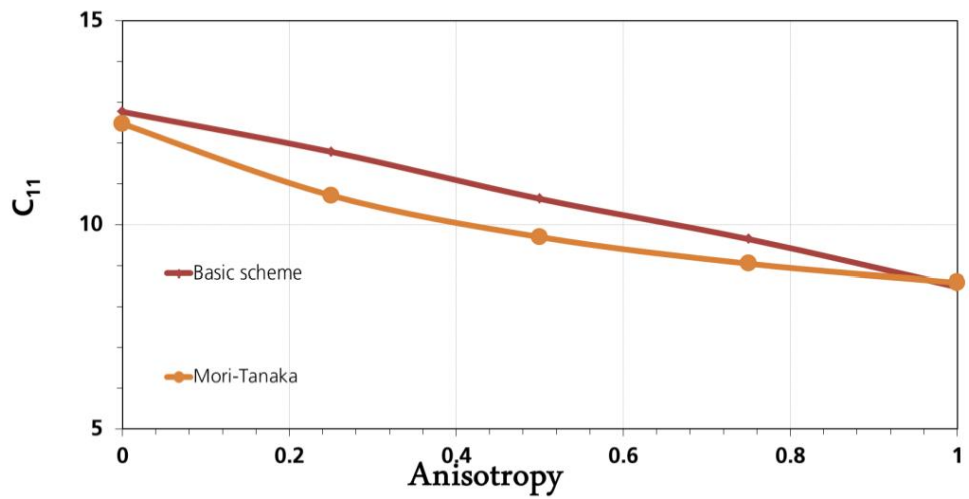


Source: PhD-Thesis, A. Radtke

Fraunhofer IWM

Short Glass-fibres in thermoplastic matrix
Effect of fibre orientation

- 1024x1024x128 Voxel
- Fibre-length 400 µm
- Structure generation with FiberGeo

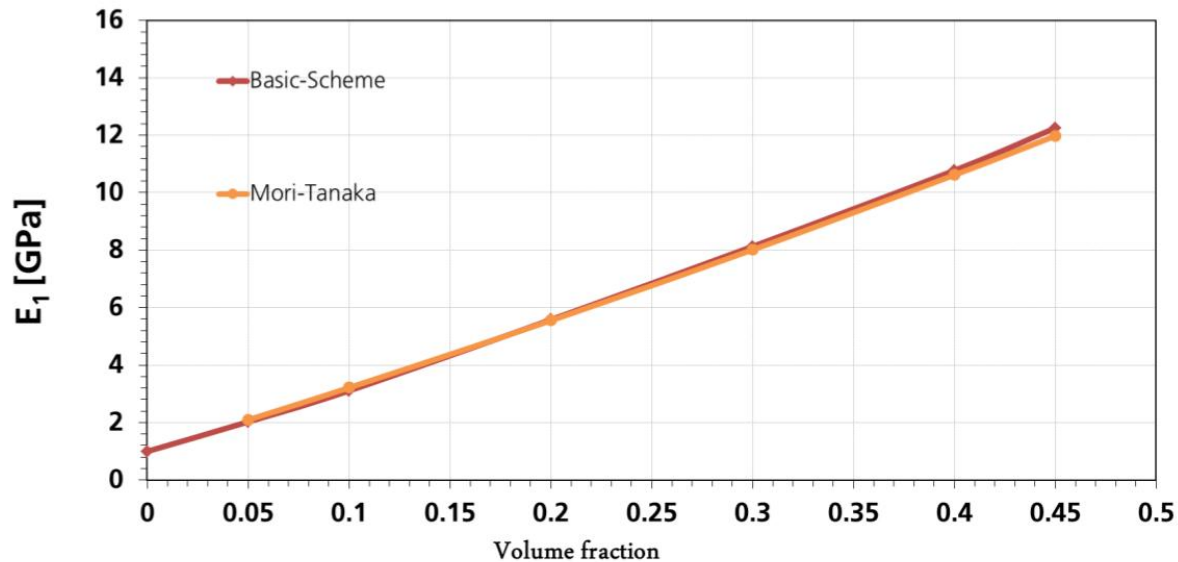


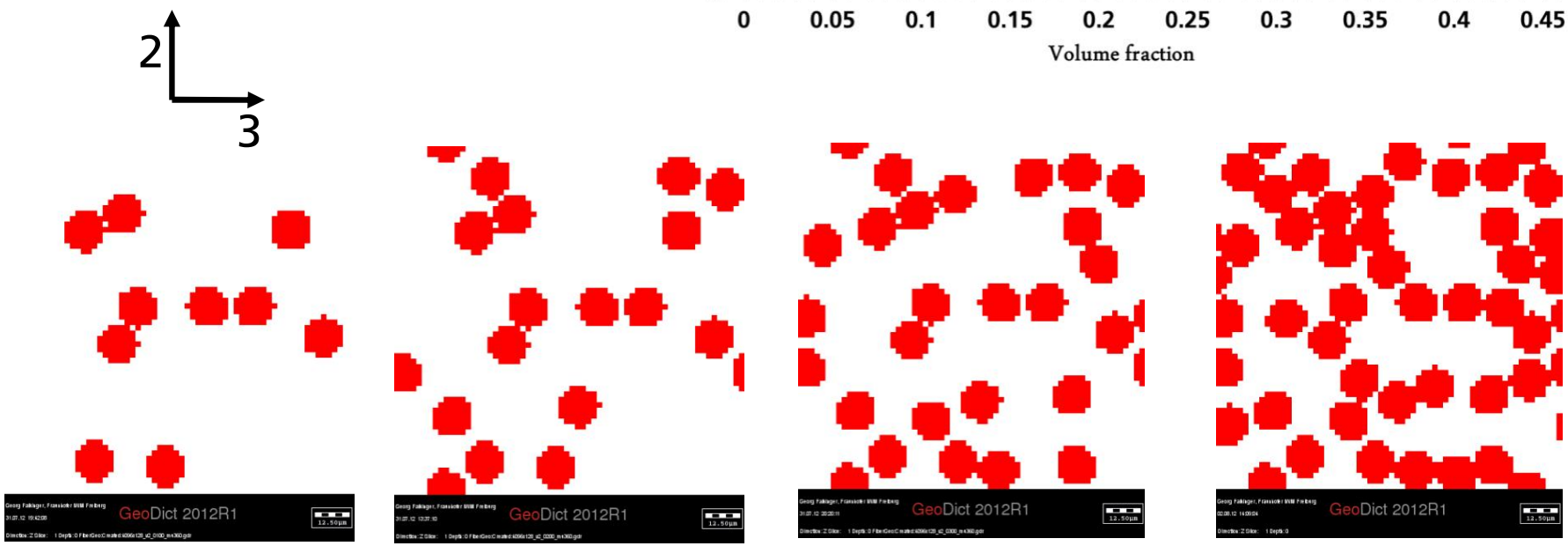
Fraunhofer IWM

Short Glass-fibres in thermoplastic matrix

Effect of fibre volume fraction

- 1024x128x128 Voxel
- Fibre-length 400 µm
- Volume Content 10%-45%
- Structure generation with FiberGeo





Fraunhofer IWM

Short Glass-fibres in thermoplastic matrix

Effect of fibre volume fraction

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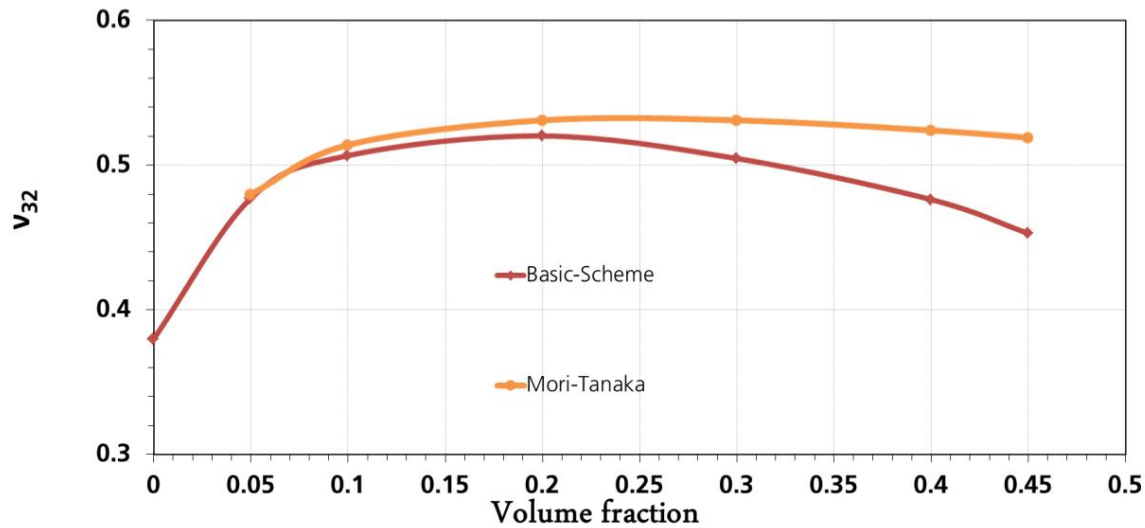
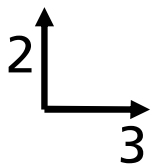
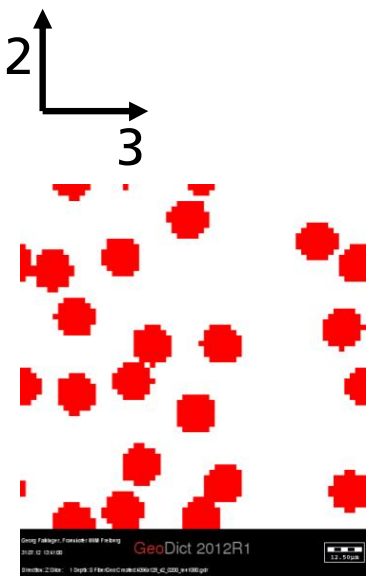


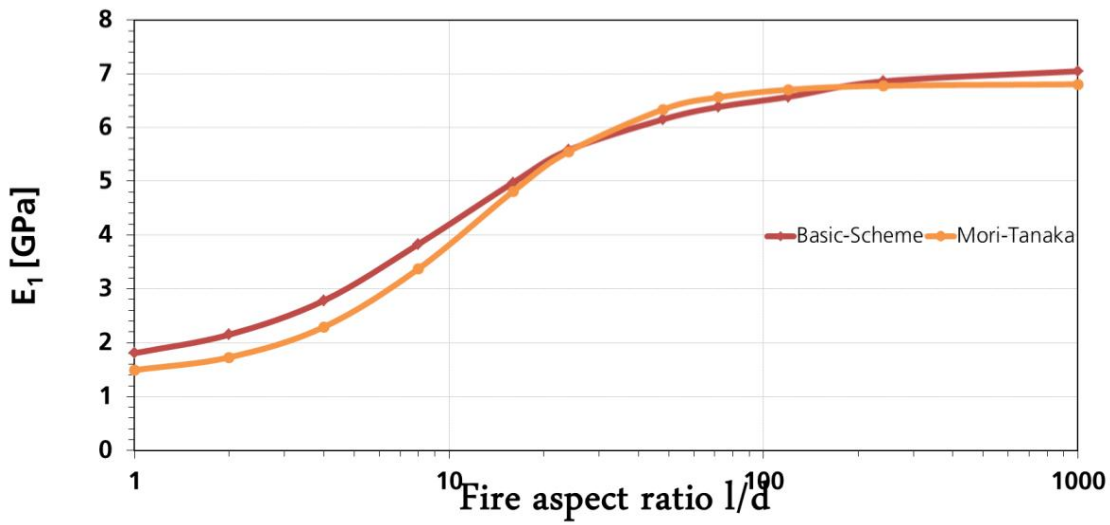


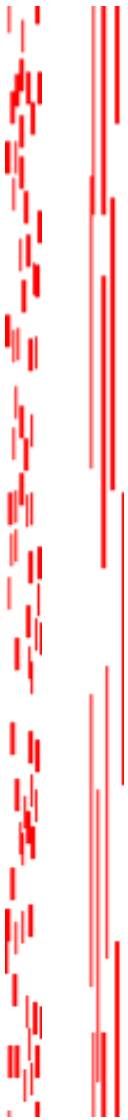
Fraunhofer IWM

Short Glass-fibres in thermoplastic matrix
Effect of fibre length

- 4096x128x128 Voxel
- Fibre Aspect-Ratio 1-200







Fraunhofer IWM

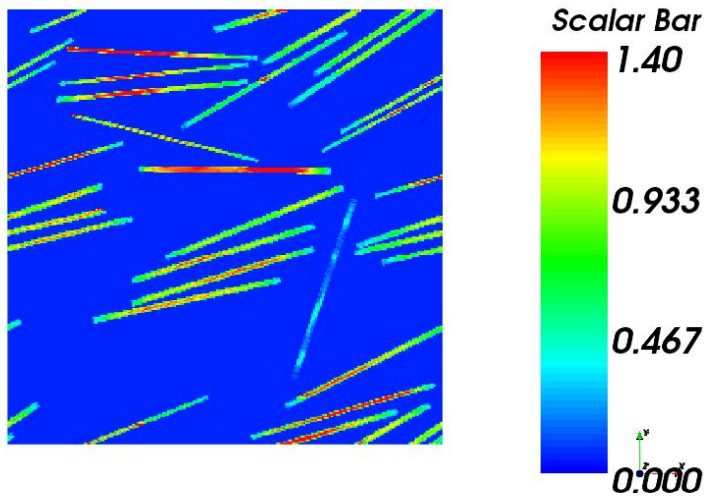
Short Glass-fibres in thermoplastic matrix

Perfect Matrix plasticity: Yieldstress 0.05 GPa

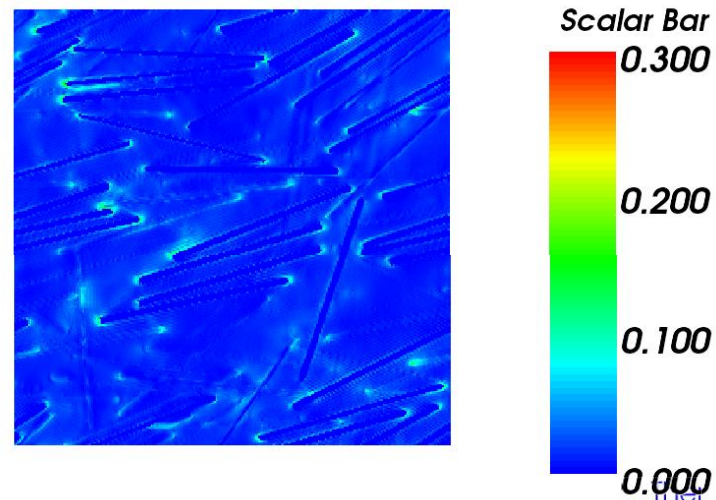
FeelMath

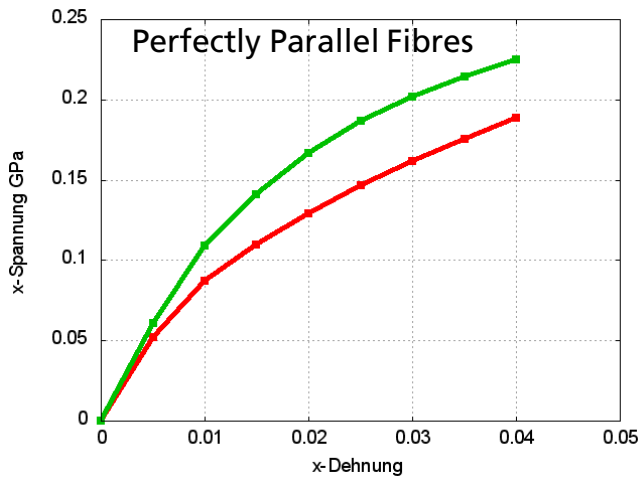
- 512x512x64 Voxel
- Voxelsize 4 µm
- Volume content 13.8%
- Fibre-length 400 µm

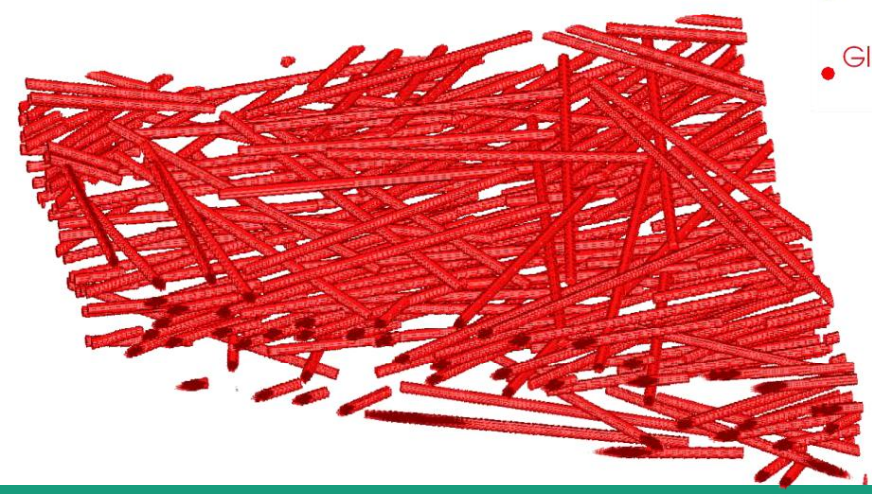
$\sigma M\ GPa$



$\varepsilon\ plastisch$







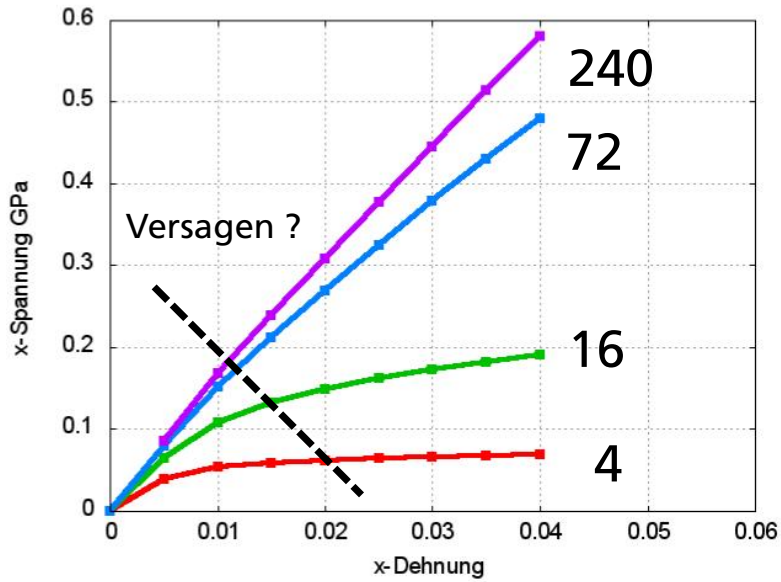
Fraunhofer IWM

Short Glass-fibres in thermoplastic matrix

Perfect Matrix plasticity: Yieldstress 0.05 GPa

- 1024x32x32 Voxel
- Voxel size 4 µm
- Volume Content 20%
- Fibre Aspect-Ratio 4-240

Fibre Aspect Ratio



Fraunhofer IWM

Summary&Outlook

- FeelMath-Vox is a very efficient tool for the prediction of effective elastic properties of Composites
- Large Structures are accessible with computations
- Faster than FEM (and less memory)
- More exact than analytical „Engineering“ formulas
- Fundamental Problem due to Voxel-Mesh: Interfaces??
- For Crash-Application elastic properties are not sufficient

Summary&Outlook

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- Faster than FEM (and less memory)
- More exact than analytical „Engineering“ formulas
- Fundamental Problem due to Voxel-Mesh: Interfaces??
- For Crash-Application elastic properties are not sufficient
  - Plastic behaviour
  - Visco-plastic behaviour
  - Damage and failure

Work in progress

Thank you very much for your attention!