e-Xstream ENGINEERING

Nonlinear Multi-scale Modeling of Rubber and Tires with DIGIMAT

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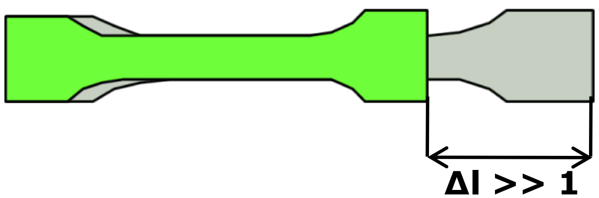
Outline

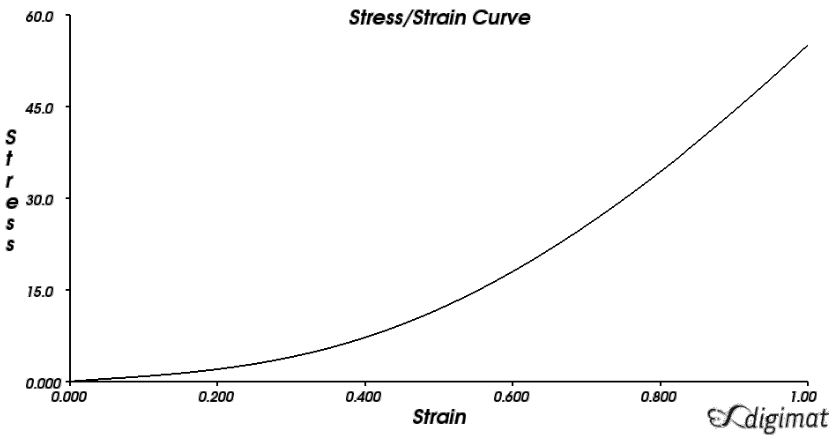
- Introduction
- DIGIMAT for Rubber Matrix Composites
  - ✓ DIGIMAT-MF: Effect of Carbon Black Content on the Rubber Stiffness (stress-Strain)
  - ✓ DIGIMAT-FE: Effect of Carbon Black Clustering on the Stress-Strain Response
  - ✓ DIGIMAT to CAE: Effect of Carbon Black on Tire Deflection & Footprint
- Conclusions

Rubber Materials

- Large deformation



- Non linear stress-strain behavior

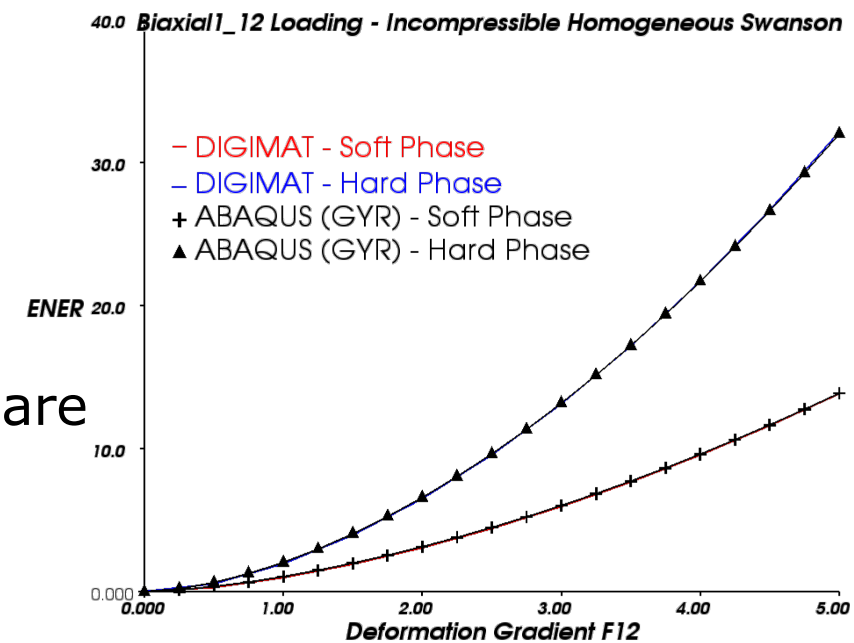


- (Quasi) Incompressible

- Applications
  - ✓ Tires
  - ✓ Anti-vibration systems
  - ✓ Seals
  - ✓ Hoses and fluid transport systems.
  - ✓ etc

Hyperelastic (Finite Strain) Material Behavior

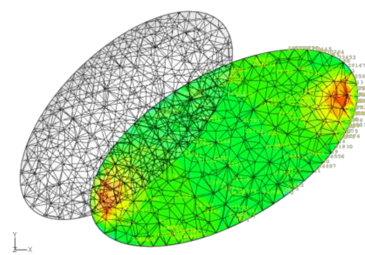
- 5 (Micro) Hyperelastic Models
  - ✓ neo-Hookean (Compressible/Incompressible)
  - ✓ Mooney-Rivlin (Compressible/Incompressible)
  - ✓ Ogden (Compressible/Incompressible)
  - ✓ Swanson (Compressible/Incompressible)
  - ✓ Storakers (Highly Compressible)
- Temperature-dependent Properties
- Verified against standard FEA Software

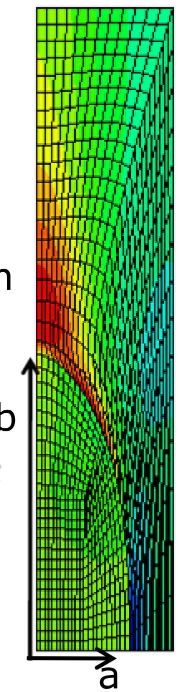


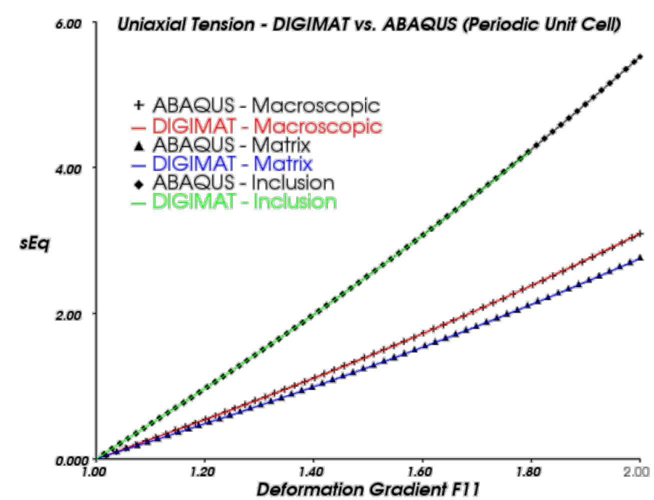
Mean-Field Homogenization of RMC

- Mean Field Homogenization (Finite Strain)
  - ✓ Mori-Tanaka
  - ✓ Interpolative Double Inclusion
- 2 to N-Phase "Composite"
  - ✓ Hyperelastic/Hyperelastic
  - ✓ Hyperelastic/Elastic
  - ✓ Hyperelastic/Rigid (Work in Progress)
  - ✓ Elastic/Hyperelastic
  - ✓ Hyperelastic/Void
- Microstructure Morphology
  - ✓ Inclusion Orientation:
    - Fixed/Random/General (Orientation Tensor)
  - ✓ Inclusion Shape
    - Platelets/Spheres/Fibers (short to continuous)
  - ✓ Inclusion Volume Fraction
    - From Low to High
- Thermo-mechanical Loading
- Verified against Unit Cell FEA

Evolution of:
- Inclusions' shape
- Inclusions' orientation

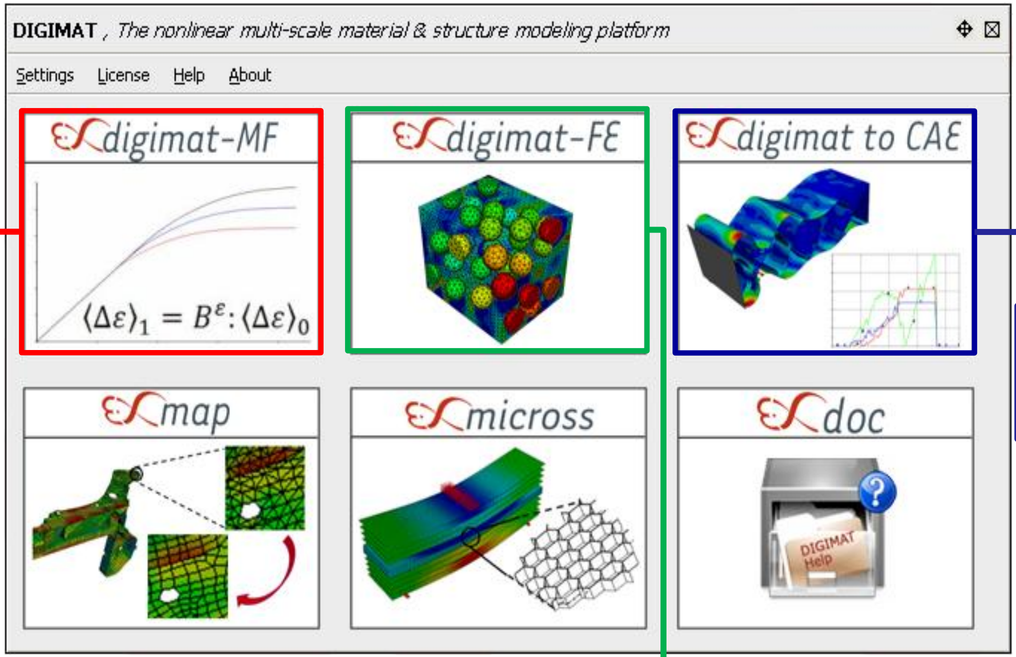






Application: Carbon Black Filled Rubber

Effect of Carbon Black Content on the Rubber Stiffness (stress-Strain)

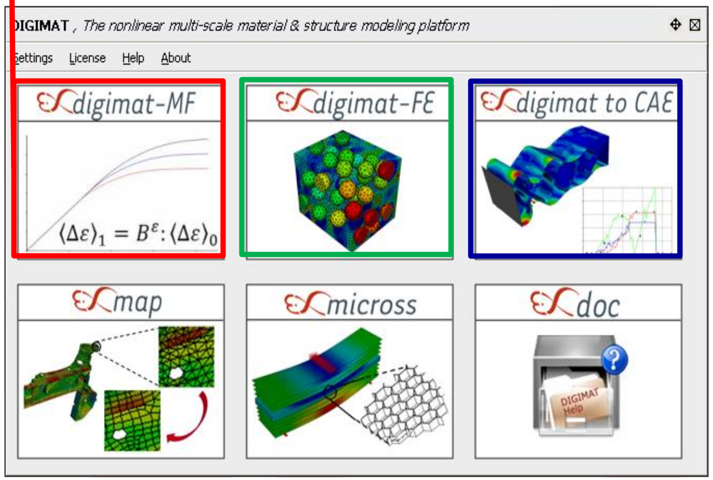


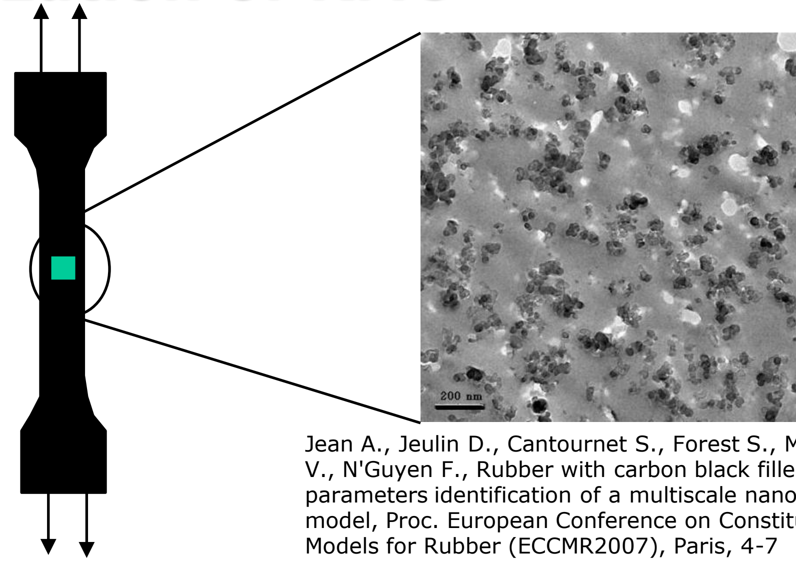
Effect of Carbon Black on Tire Deflection & Footprint

Effect of Carbon Black Clustering on the Stress-Strain Response

Mean-Field Homogenization of RMC

Effect of Carbon Black Content on the Rubber Stiffness (stress-Strain)

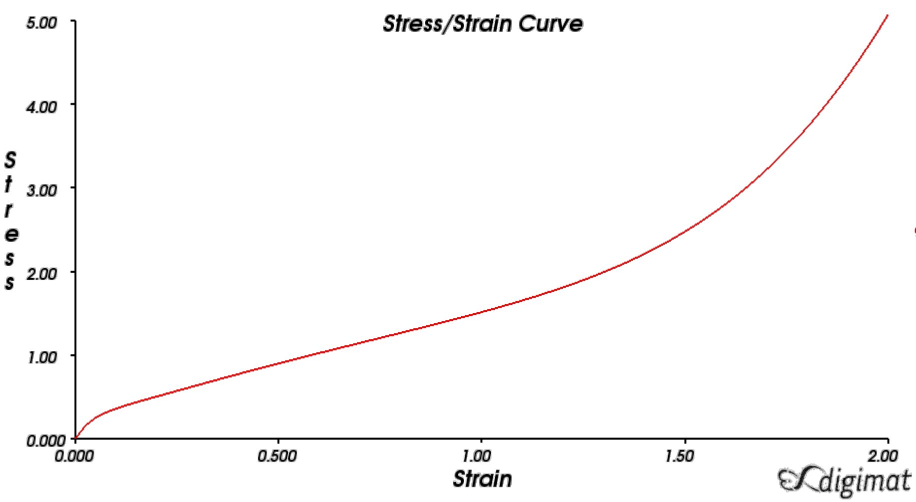




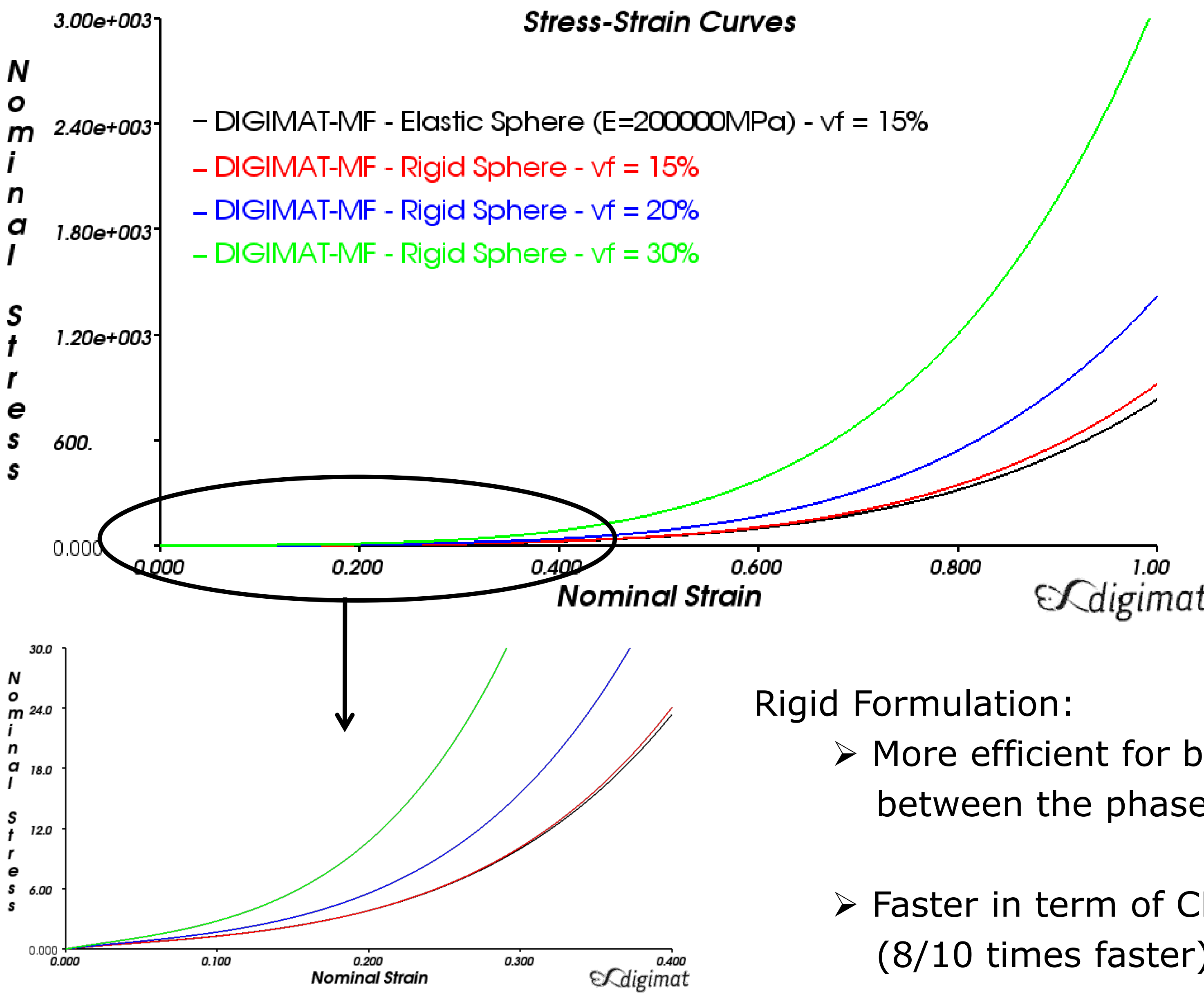
Jean A., Jeulin D., Cantournet S., Forest S., Mounoury V., N'Guyen F., Rubber with carbon black fillers: parameters identification of a multiscale nanostructure model, Proc. European Conference on Constitutive Models for Rubber (ECCMR2007), Paris, 4-7 September 2007

- Morphological analysis on the microstructure
  - Matrix: Rubber
    - ✓ Hyperelastic law : Ogden (N=3)

    (Coefficients fitted on experimental stress – strain curve)
  - Inclusion: Carbon Black
    - ✓ Young Modulus = 200,000 MPa
    - ✓ Poisson ratio = 0.3
    - ✓ Volume fraction = 15%
    - ✓ Aspect ratio = 1 (Sphere)



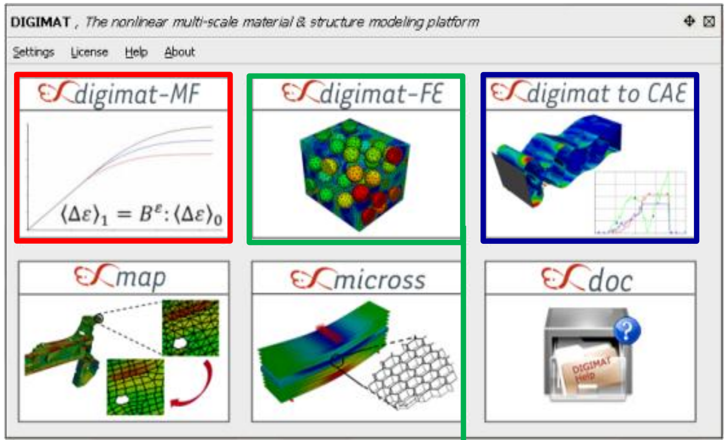
Effect of Carbon Black Volume Fraction on S-S Curves



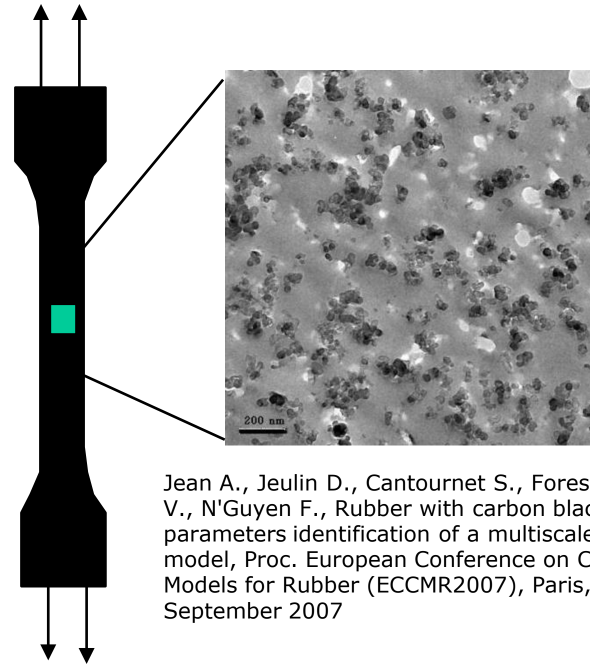
Rigid Formulation:

- More efficient for big contrast between the phases
- Faster in term of CPU Times (8/10 times faster)

Carbon Black Clustering

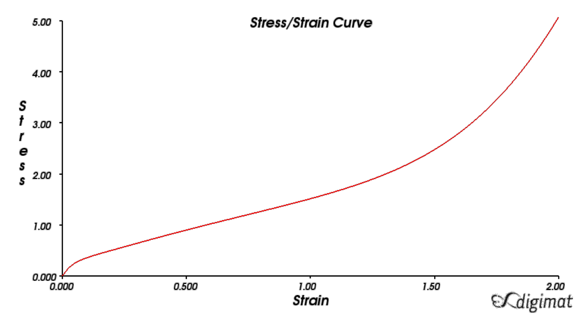


Effect of Carbon Black Clustering



Jean A., Jeulin D., Cantournet S., Forest S., Mounoury V., N'Guyen F., Rubber with carbon black fillers: parameters identification of a multiscale nanostructure model, Proc. European Conference on Constitutive Models for Rubber (ECCMR2007), Paris, 4-7 September 2007

- ❑ Morphological Analyses of the real microstructure
  - ➢ Phase distribution : clusters or random
  - ➢ Inclusions' shape : Spheres (Assume to be of the same size)

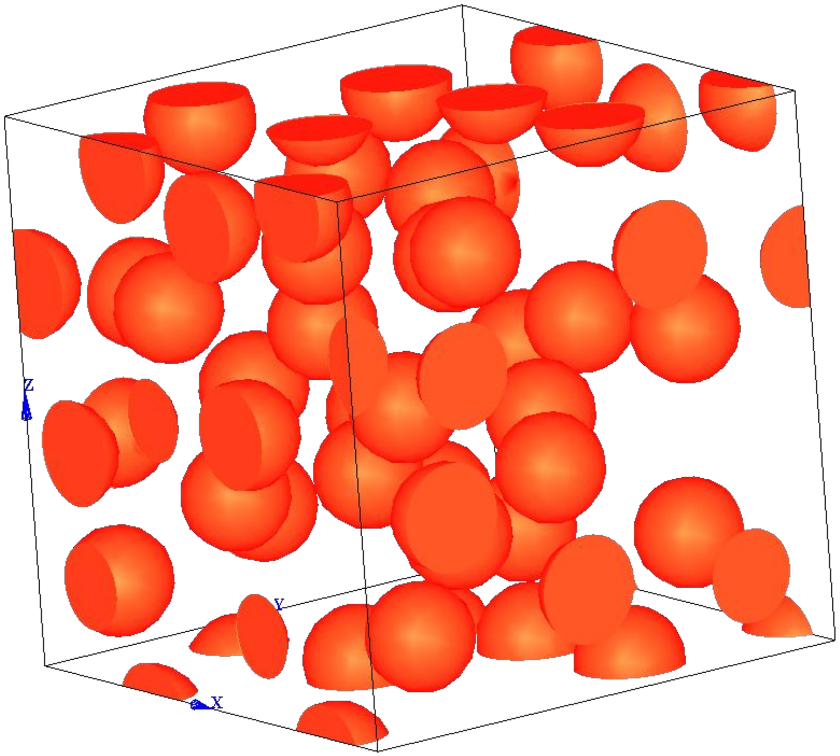


- ❑ Constituent properties
  - ➢ Matrix: Rubber
    - ✓ Hyperelastic law : Ogden (N=3)

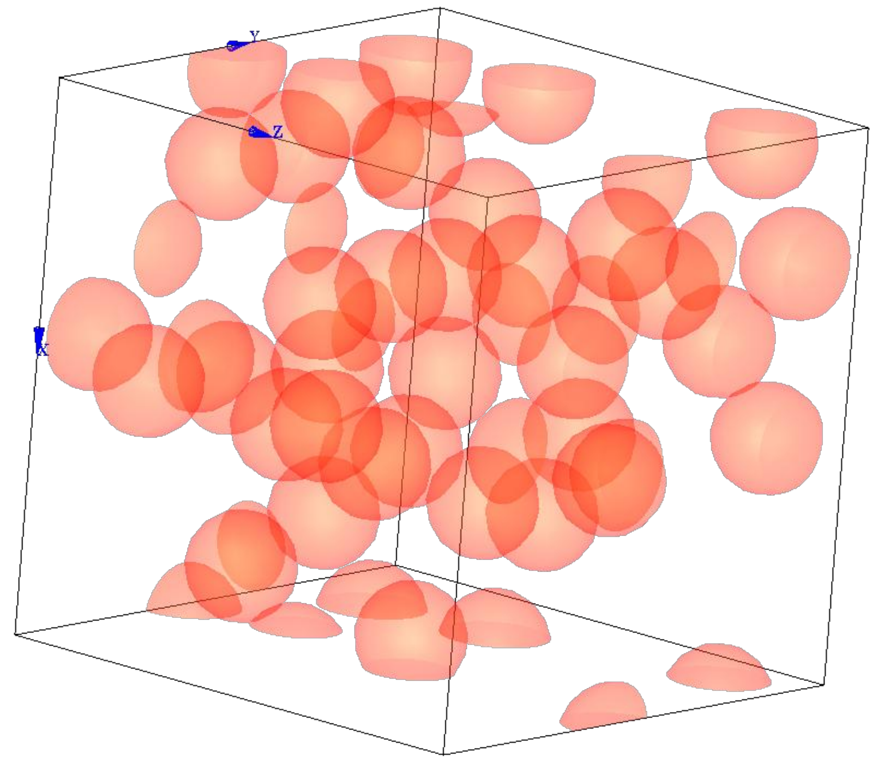
    (Coefficients fitted on experimental stress – strain curve)
  - ➢ Elastic Inclusions (Carbon Black) -> Big contrast between phase properties

Representative Volume Element Geometry

Microstructure without clusters
(random distribution of inclusions)



Microstructure with Clusters

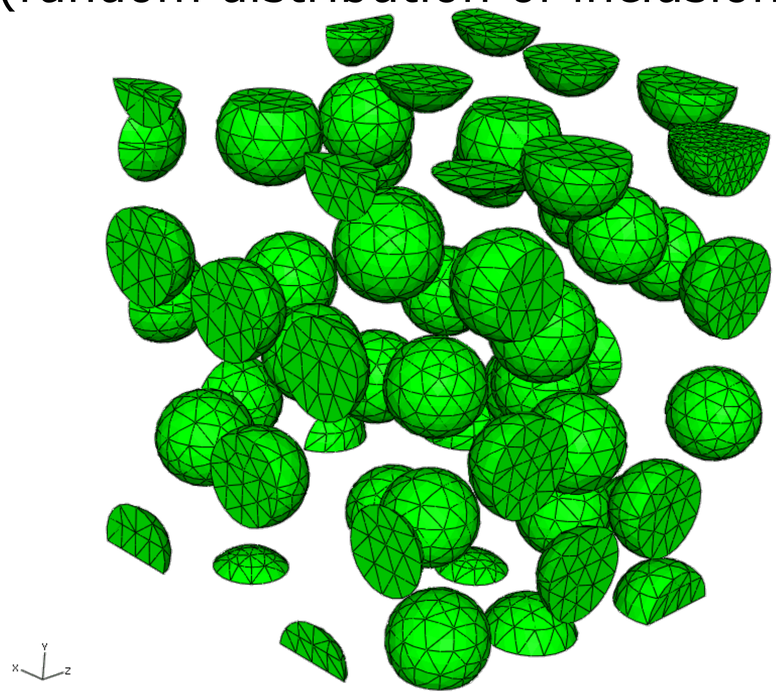


For both microstructures :

- Number of inclusions = 30
- Same size for each inclusion

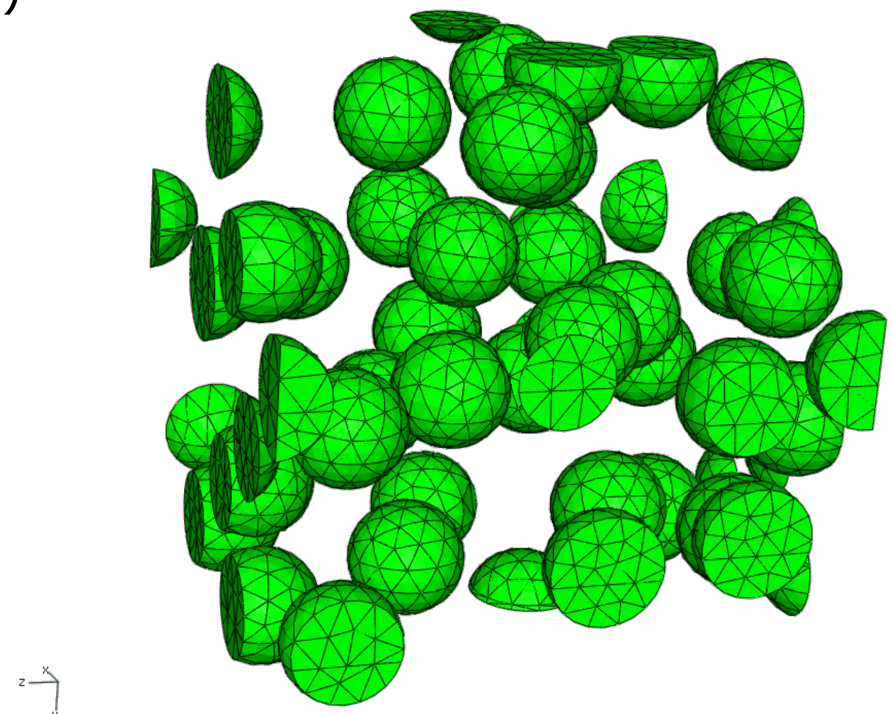
Automatic RVE Meshing with DIGIMAT-FE to ABAQUS/CAE

Microstructure without clusters (random distribution of inclusions)



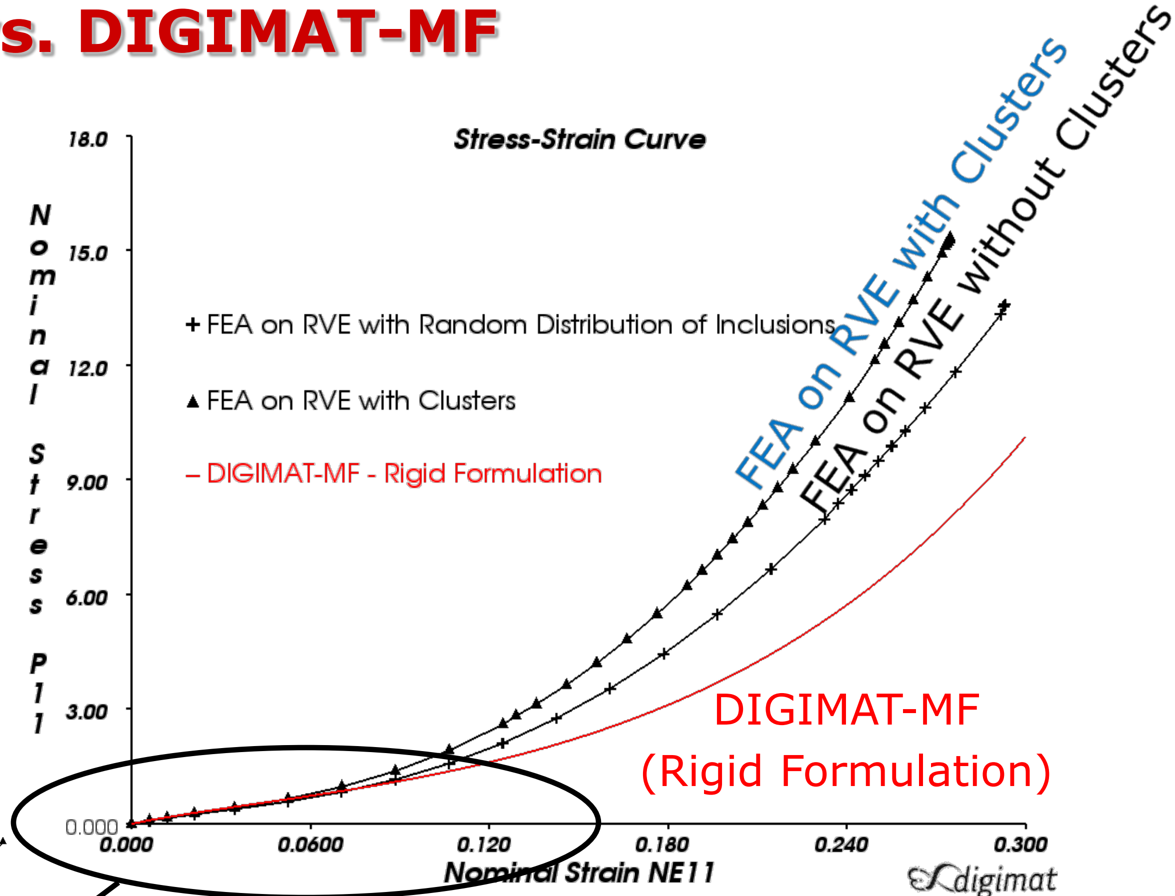
- Element Type:
  - C3D10M for Inclusion
  - C3D10MH for the matrix
- Number of Element = 66,917

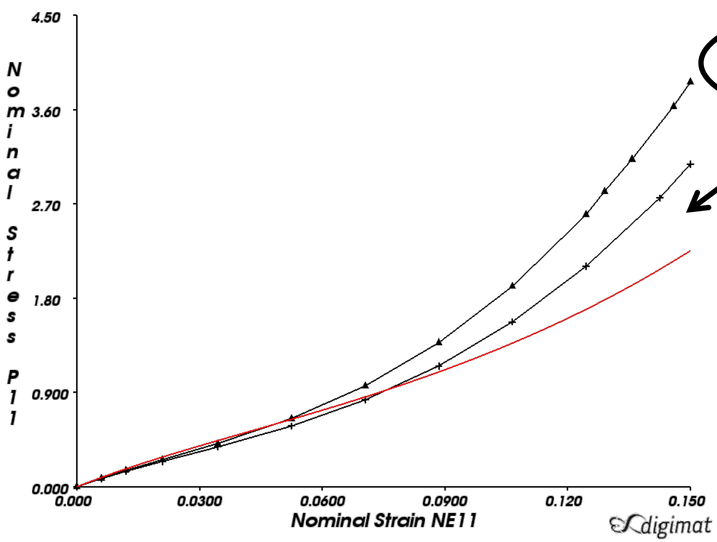
Microstructure with Clusters



- Element Type:
  - C3D10M for Inclusion
  - C3D10MH for the matrix
- Number of Element = 64,165

FEA on RVE vs. DIGIMAT-MF





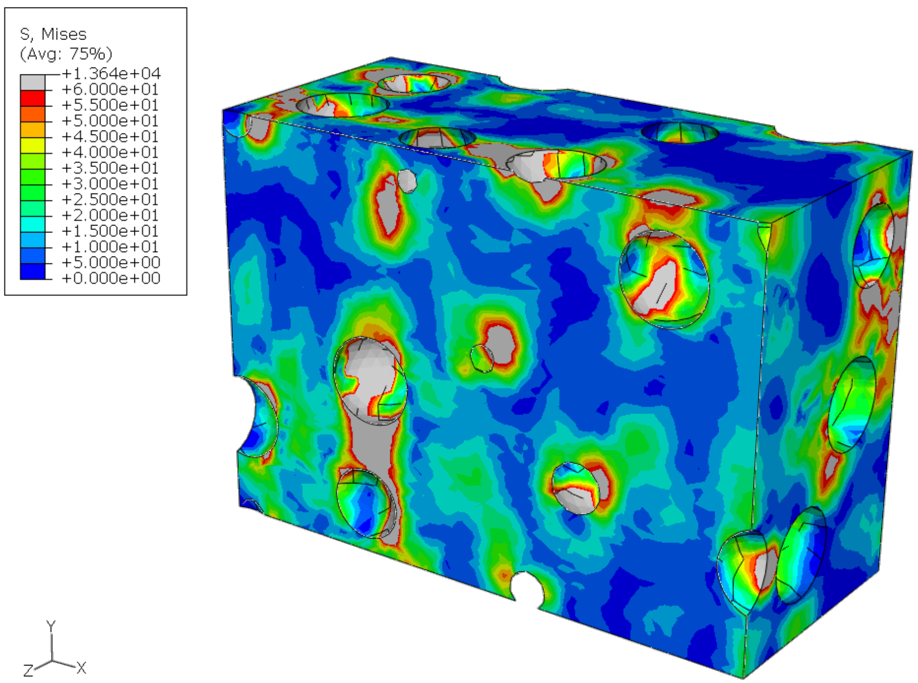
Relative Difference:

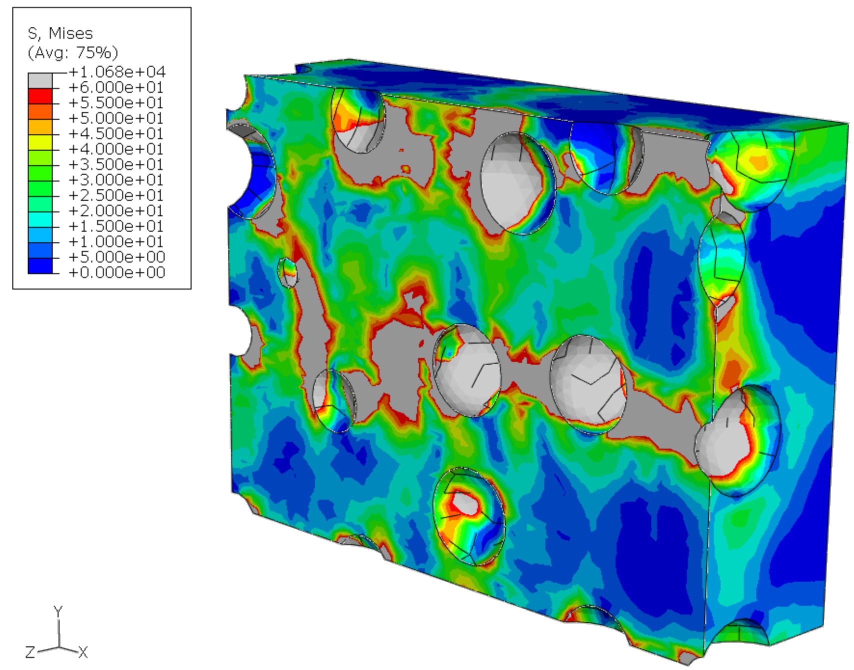
- Microstructure without clusters :
  - For NE11 = 10% -> Diff ~ 10%
  - For NE11 = 20% -> Diff ~ 38%
- Microstructure with clusters :
  - For NE11 = 10% -> Diff ~ 27%
  - For NE11 = 20% -> Diff ~ 45%

Stress Distribution in the Rubber Matrix

Microstructure without Clusters
(random distribution of inclusions)

Microstructure with Clusters



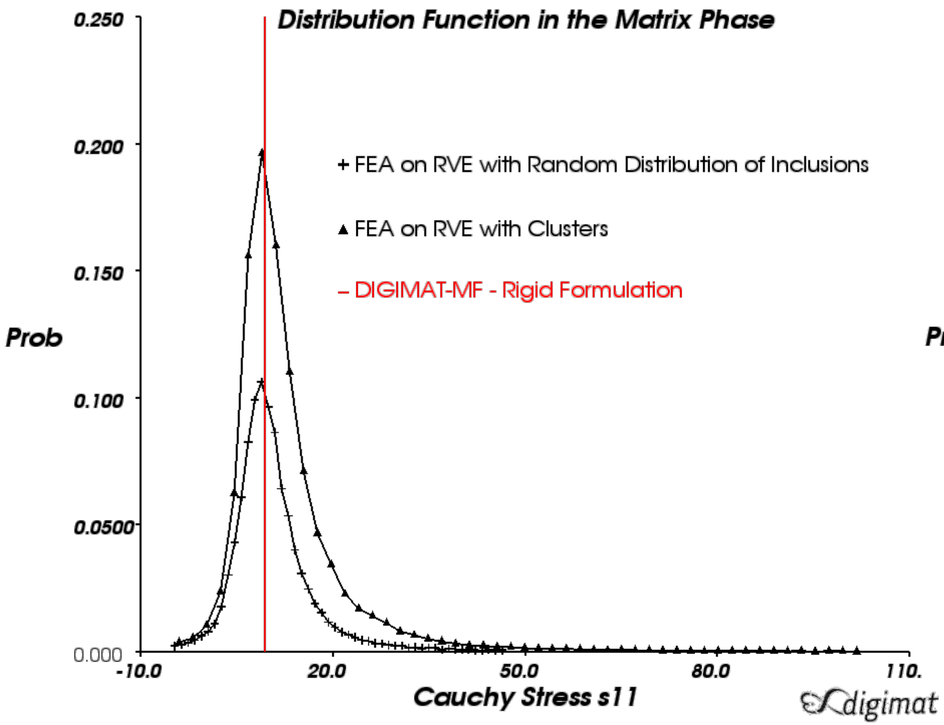


Snapshot of local von-Mises stress for a nominal strain of 27%

Difference on Maximum Stress between microstructure with clusters and microstructure without clusters = 60%

Local Fields Distribution in the Matrix Phase

Cauchy Stress Tensor



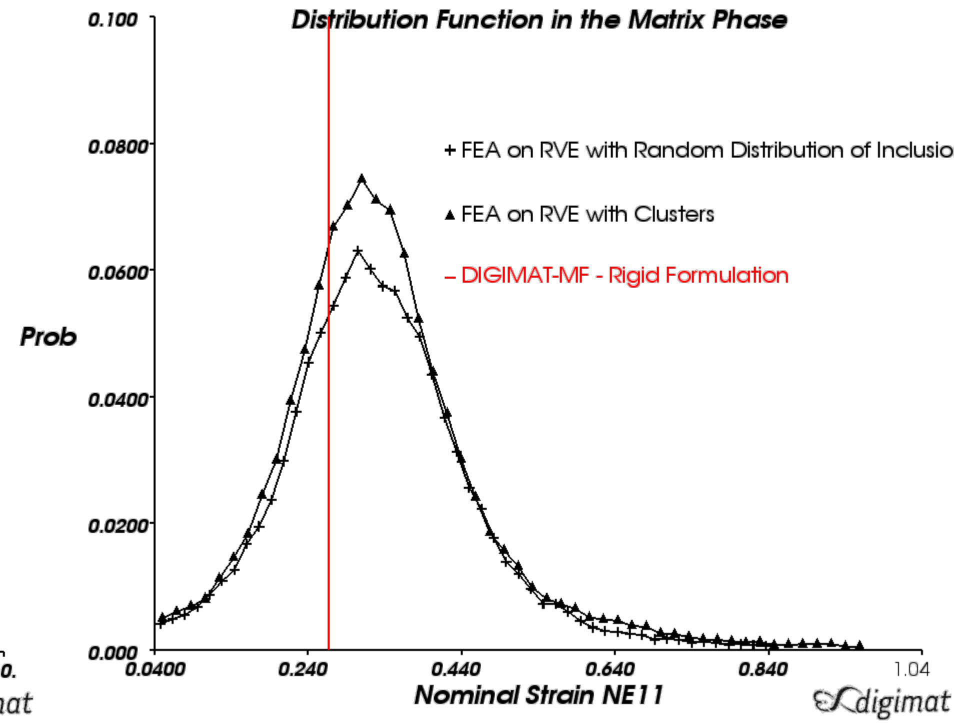
Microstructure without clusters :

- Min stress = -4.67 MPa
- Max stress = 46.43 MPa

Microstructure with clusters :

- Min stress = -3.97 MPa
- Max stress = 101.75 MPa

Nominal Strain Tensor



Microstructure without clusters :

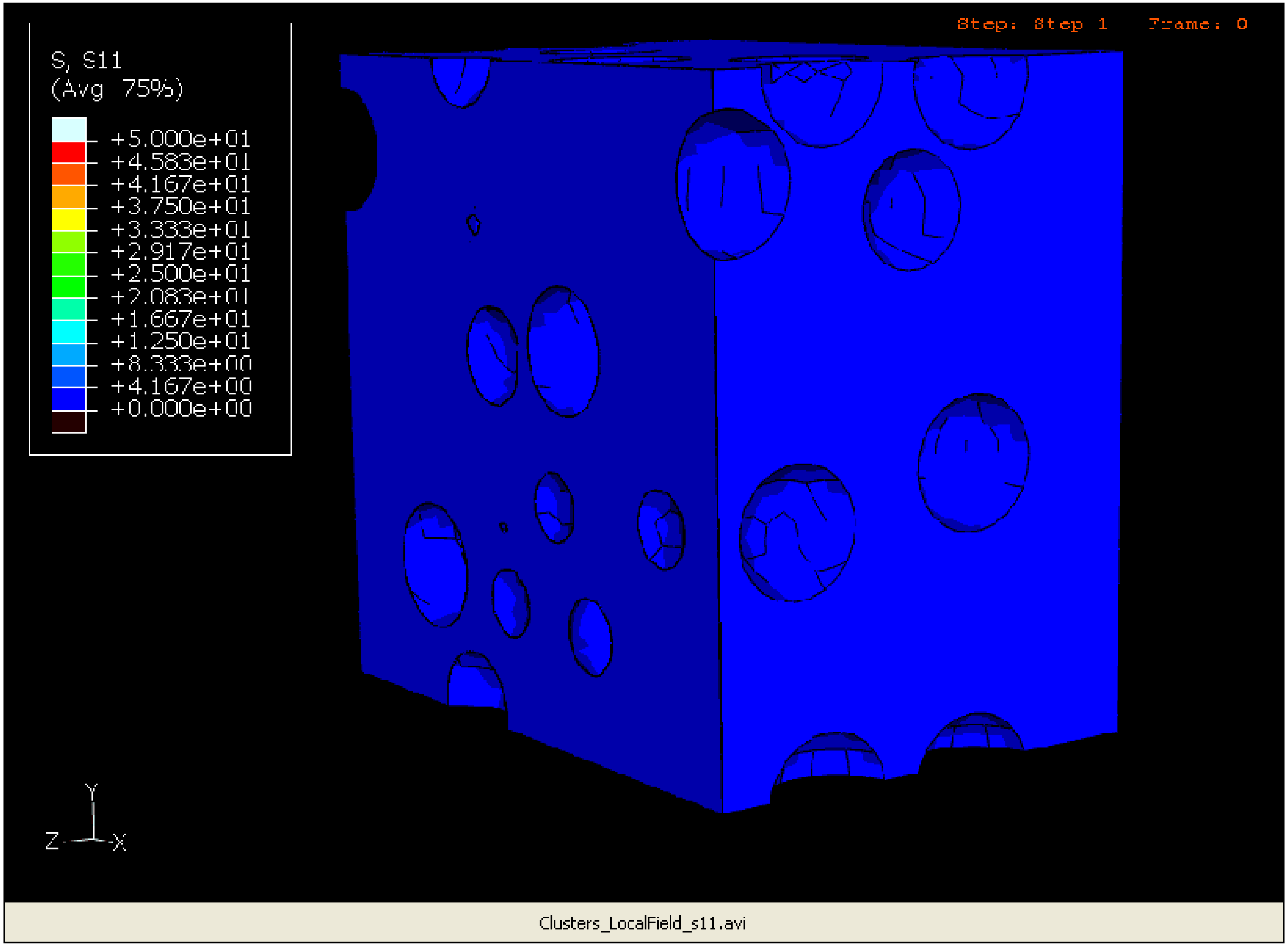
- Min strain = 4.73%
- Max strain = 83.63%

Microstructure with clusters :

- Min strain = 5.02%
- Max strain = 95.87%

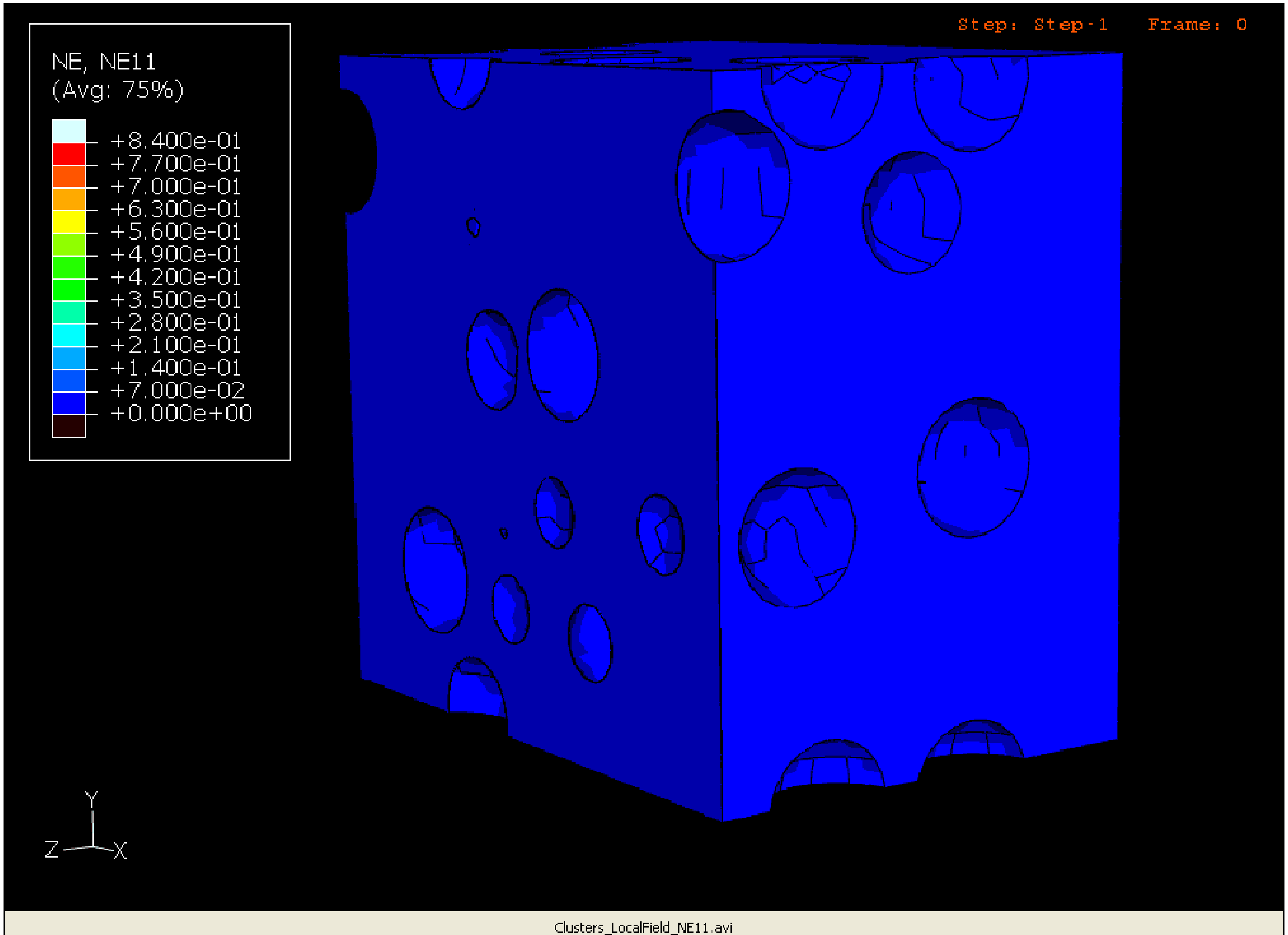
Distribution function for a macroscopic nominal strain = 27%

Evolution of Stress/Strain in the Matrix Phase during the loading (1)



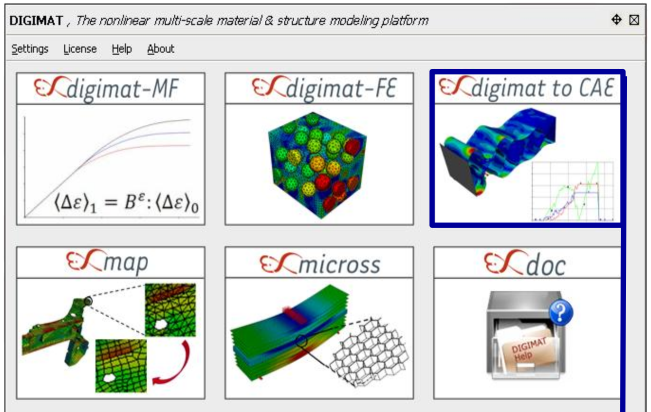
Cauchy Stress Tensor

Evolution of Stress/Strain in the Matrix Phase during the loading (2)



Nominal Strain Tensor

Effect to Carbon Black on Tire Deflection & Footprint

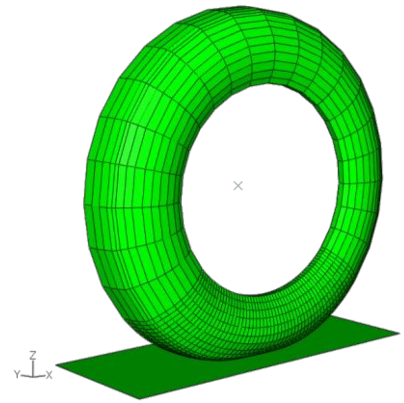


Effect of Carbon Black Content on Tire Deflection & Footprint

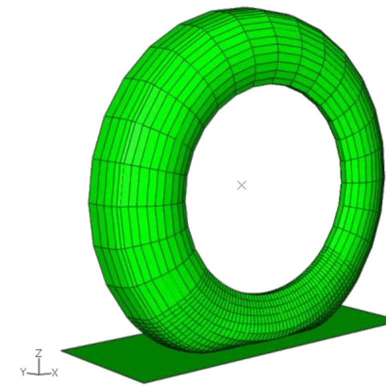
Use DIGIMAT to CAE:

- Morphology effect on the global/Local response of a tire model under two different configurations:

Vehicle loading = 1640 N

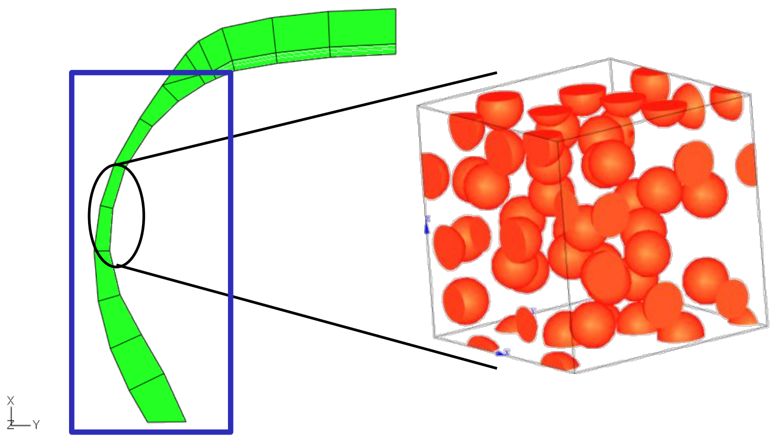


Inflation Mode
Pressure = 2 Bars



Deflation Mode
Pressure = 0 Bar

<u>Source:</u> Abaqus Users' Manual



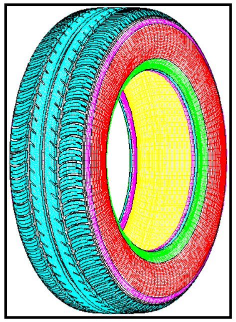
DIGIMAT-MF
(Rigid formulation)

FEA of the Tire are performed:

- on a Linux 64 bits machine
- on a single processor

Interaction between DIGIMAT and FEA

Classical FE process

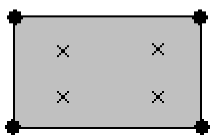


FE model level

Nodal coordinates, …

Internal forces and element stiffness

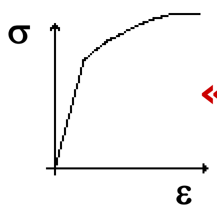
Element level



Strain increments, material state, …

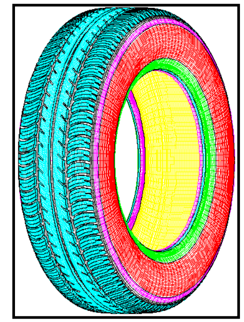
Stresses and material stiffness

Material level



« In code » model

Coupled FE/DIGIMAT process

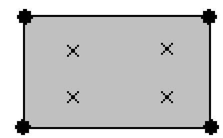


FE model level

Nodal coordinates, …

Internal forces and element stiffness

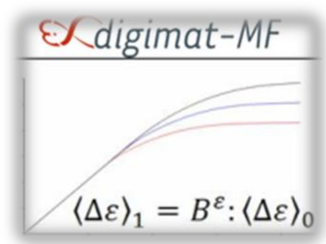
Element level



Strain increments, material state, …

Stresses and material stiffness

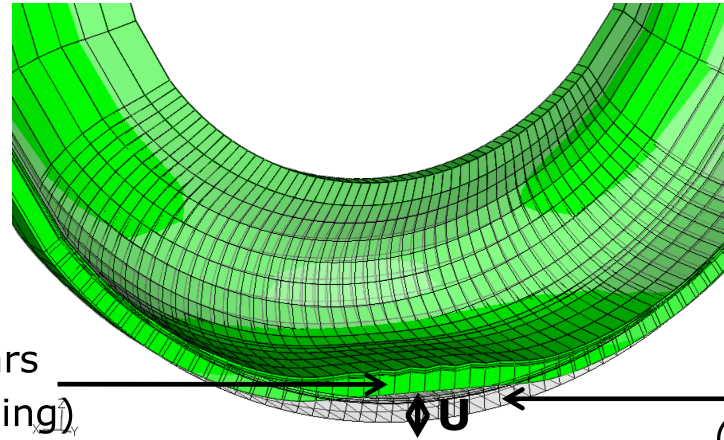
Material level



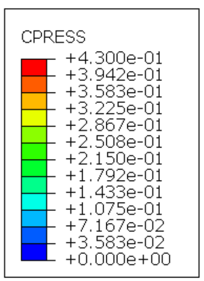
Tire Deflection & Footprint @ 2 bars

Homogeneous Matrix
- U=19.3 mm
- CPU=132 s

Pressure = 2 Bars
(With vehicle loading)

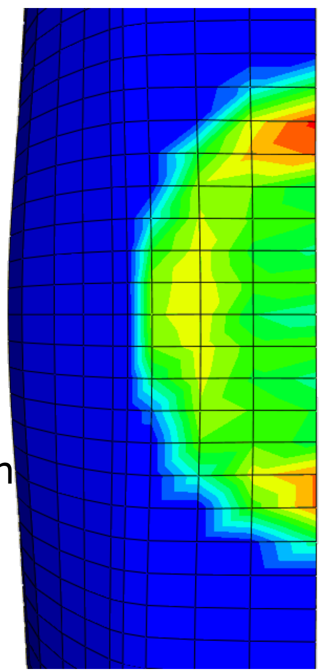


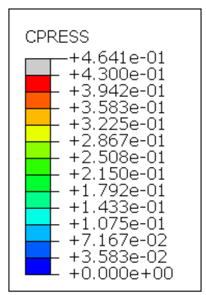
Pressure = 2 Bars
(Without vehicle loading)



vf=15%

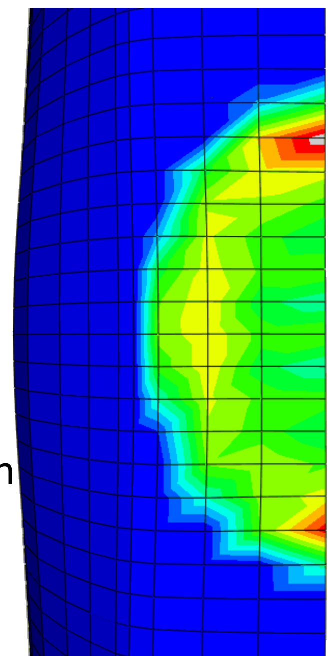
U=19.82 mm

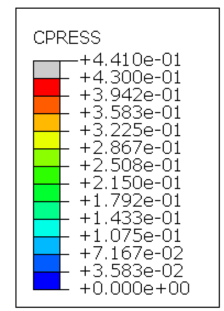




vf=20%

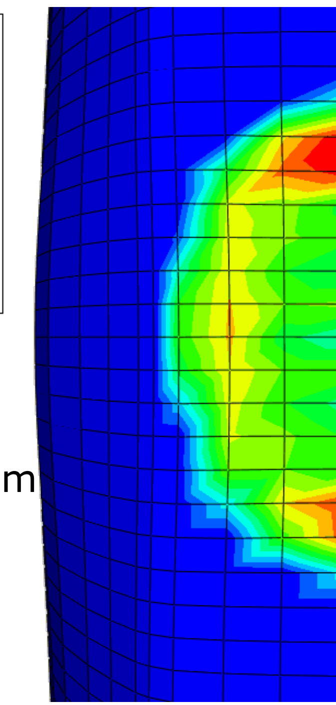
U=19.83 mm





vf=30%

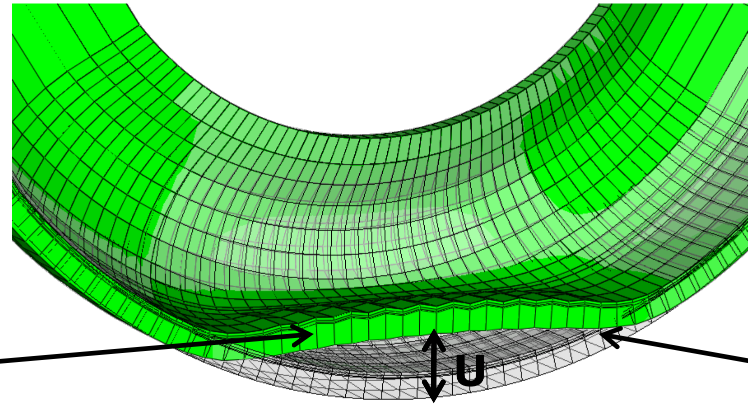
U=19.85 mm



Tire Deflection & Footprint @ 0 bar

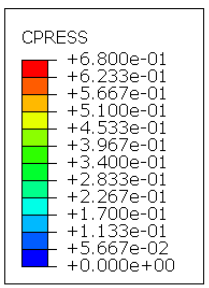
Homogeneous Matrix

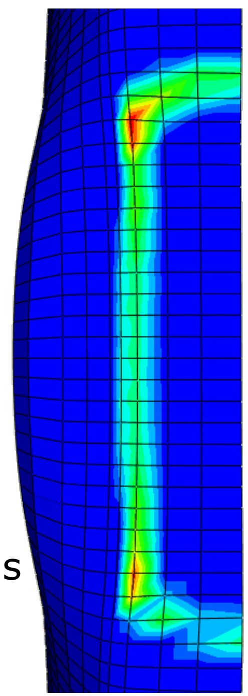
- U=51.55 mm
- CPU=132 s



Pressure = 0 Bar (With vehicle loading)

Pressure = 2 Bars (Without vehicle loading)

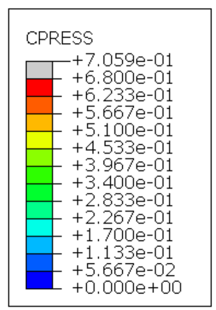


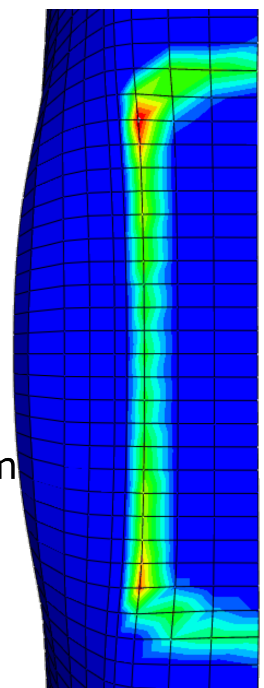


vf=15%

U=44.38 mm

CPU=841.44 s

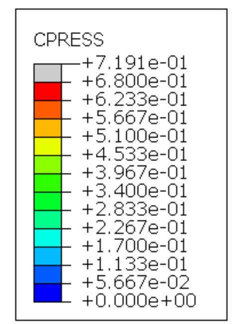


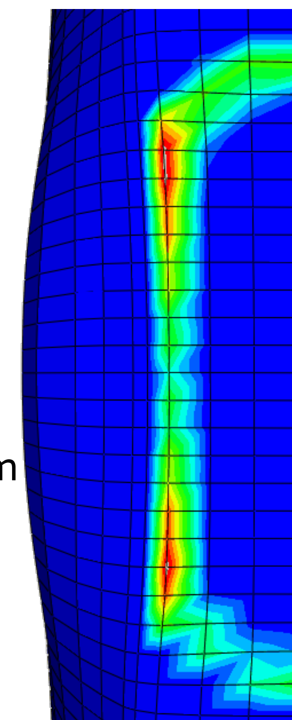


vf=20%

U=41.27 mm

CPU=1293 s



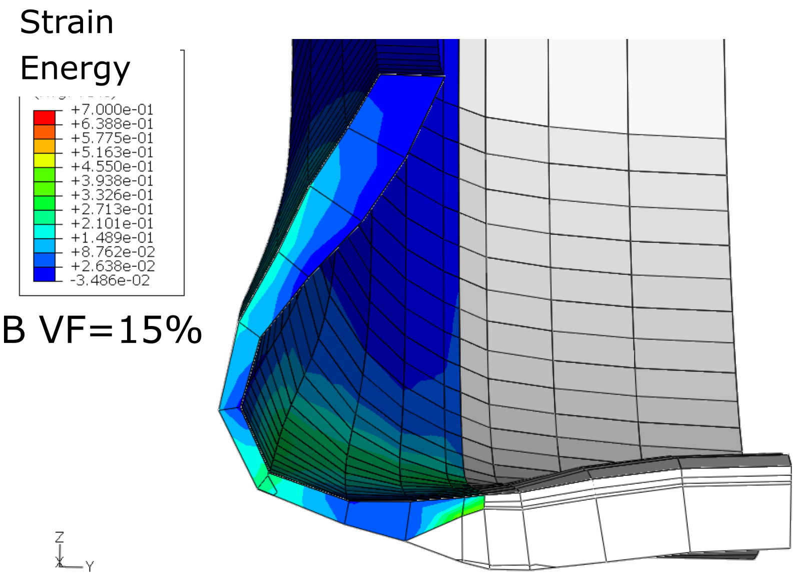


vf= 30%

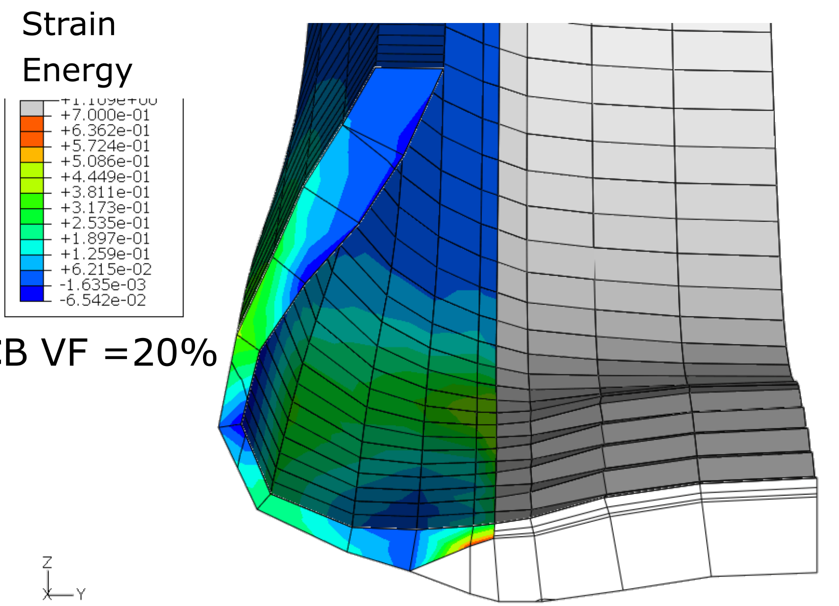
U=34.26 mm

CPU=1193 s

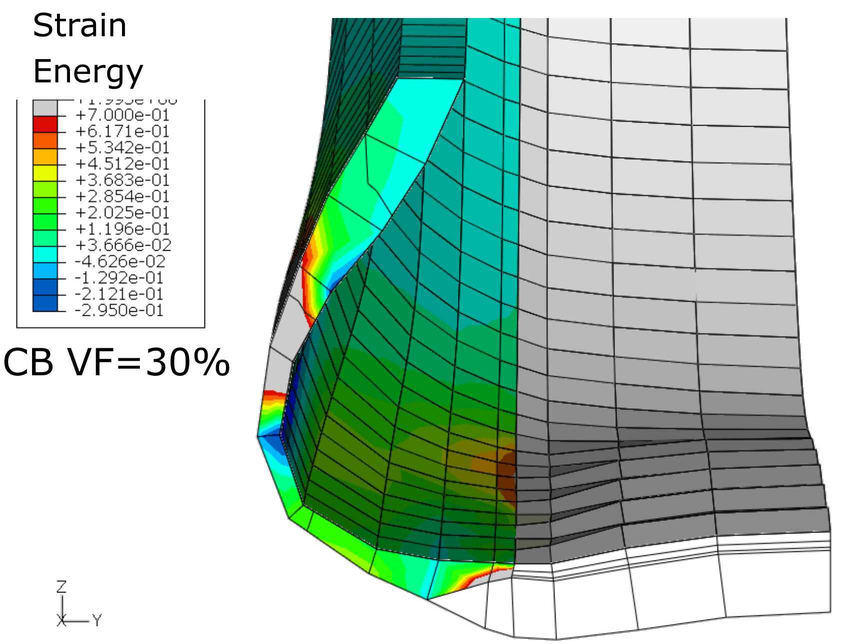
Strain Energy in the Rubber Matrix



CB VF=15%



CB VF =20%



CB VF=30%

Conclusions

- DIGIMAT-MF
  - ✓ Computes the nonlinear behavior of RMC as a function of the underlying microstructures
  - ✓ A “RIGID” formulation was developed to better deal with very stiff inclusions
    - Minimizes CPU costs & Improves Convergence
    - Limited to spherical inclusions. The extension to fibers is ongoing
  - ✓ Limited to random distribution of inclusions
- DIGIMAT-FE
  - ✓ Predicts detailed information in the microstructure
  - ✓ Tale into account the exact inclusion distribution (e.g. clustering)
- DIGIMAT to CAE
  - ✓ Use Mean-Field homogenization at the microscale
  - ✓ Enables a strong coupling between the material microstructure and the behavior of the rubber structure

Acknowledgments: e-Xstream would link thank Goodyear and the Luxembourg Ministry of Economy for supporting the R&D work performed in the field of nonlinear mean-field homogenization of Rubber Matrix Composites.