DIGIMAT Multi-Scale Modeling: The Technology & Software Tools for a Predictive Development of Reinforced Plastic Parts

Roger A. Assaker

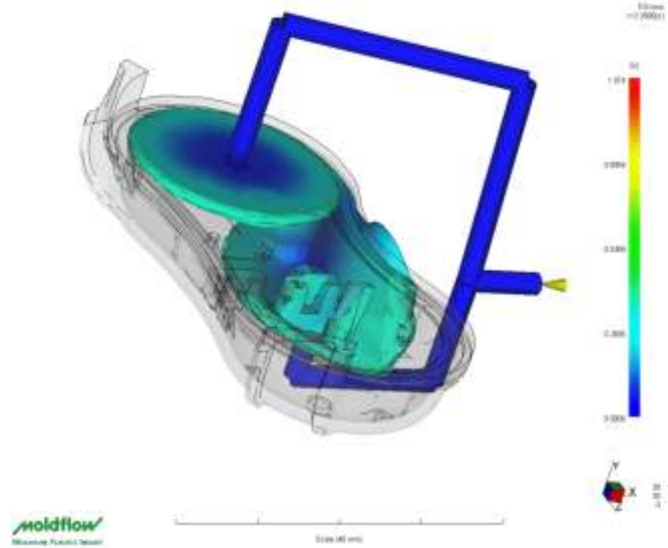
Roger.assaker@e-Xstream.com

Skype: eX_RAR

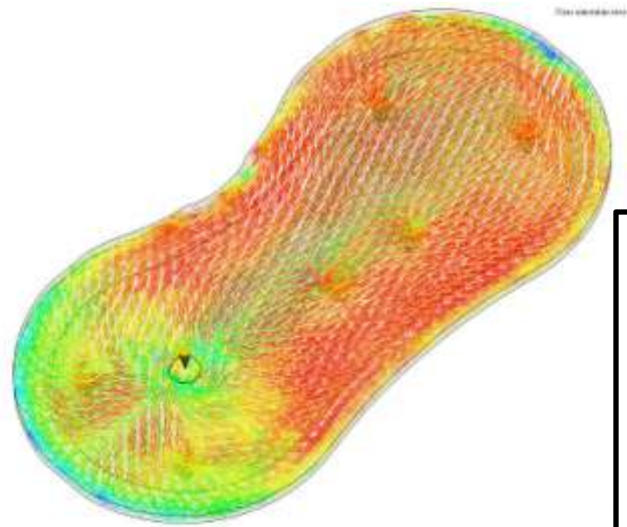
Mobile: +32 495 52 56 52

www.e-Xstream.com

The Problem: Fiber Orientation & the Underlying Material Behavior (<u>Simplified</u>)

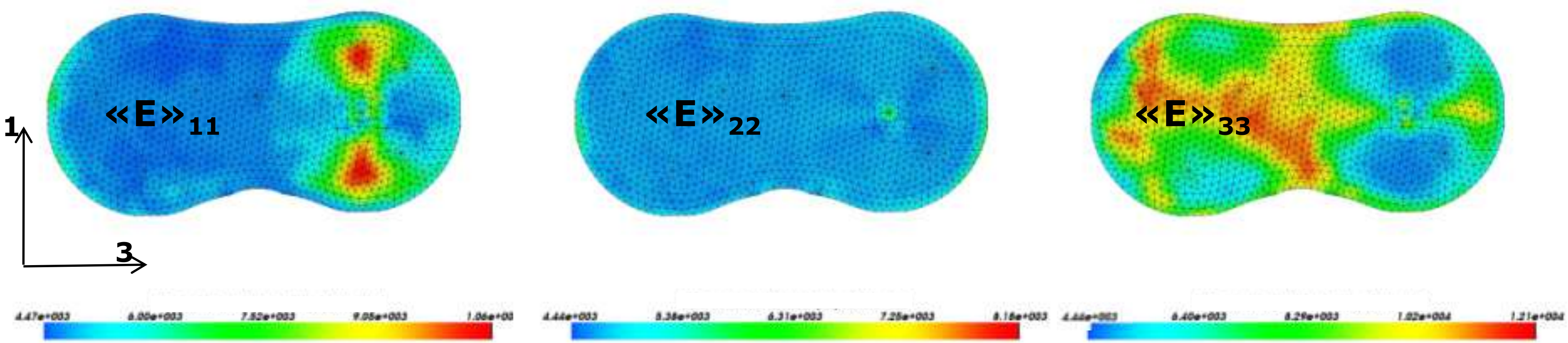


Courtesy of **SOLVAY**



PA Matrix
- E = 3150 Mpa
- Nu = 0.36
- Density = 1220 kg/m^3

Glass Fibers
- E = 71 200 Mpa
- Nu = 0.22
- Density = 2600 kg/m^3
- Weight fraction = 0.33

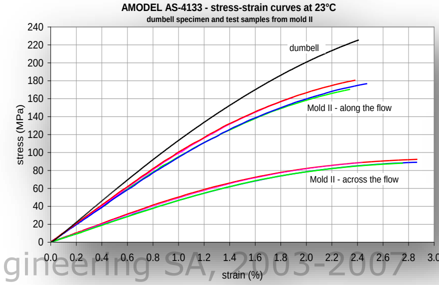


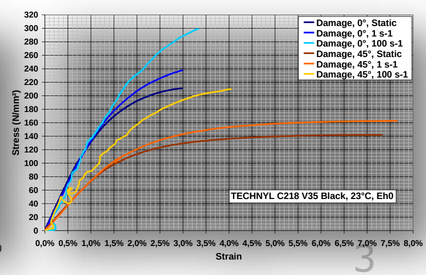
4,470 MPa → 10,600 MPa **4,440 MPa → 8,180 MPa** **4,440 MPa → 12,100 MPa**

Realistic FEA of the Reinforced Plastic Parts

- Software Choice
- Geometric nonlinearities (Large Deformations)
- Contact
- Implicit/Explicit integration
- Optimal mesh refinement
- Optimal element choice
  - ✓ 1st/2nd order
  - ✓ Tet or Hex, Triangle or Quad
- **Material → Reinforced Plastic**
  - ✓ Anisotropic
  - ✓ Heterogeneous
  - ✓ Nonlinear
  - ✓ Rate-dependent
  - ✓ Damage
  - ✓ Fatigue
  - ✓ Failure
  - ✓ Etc.

→ Which Material Model ?

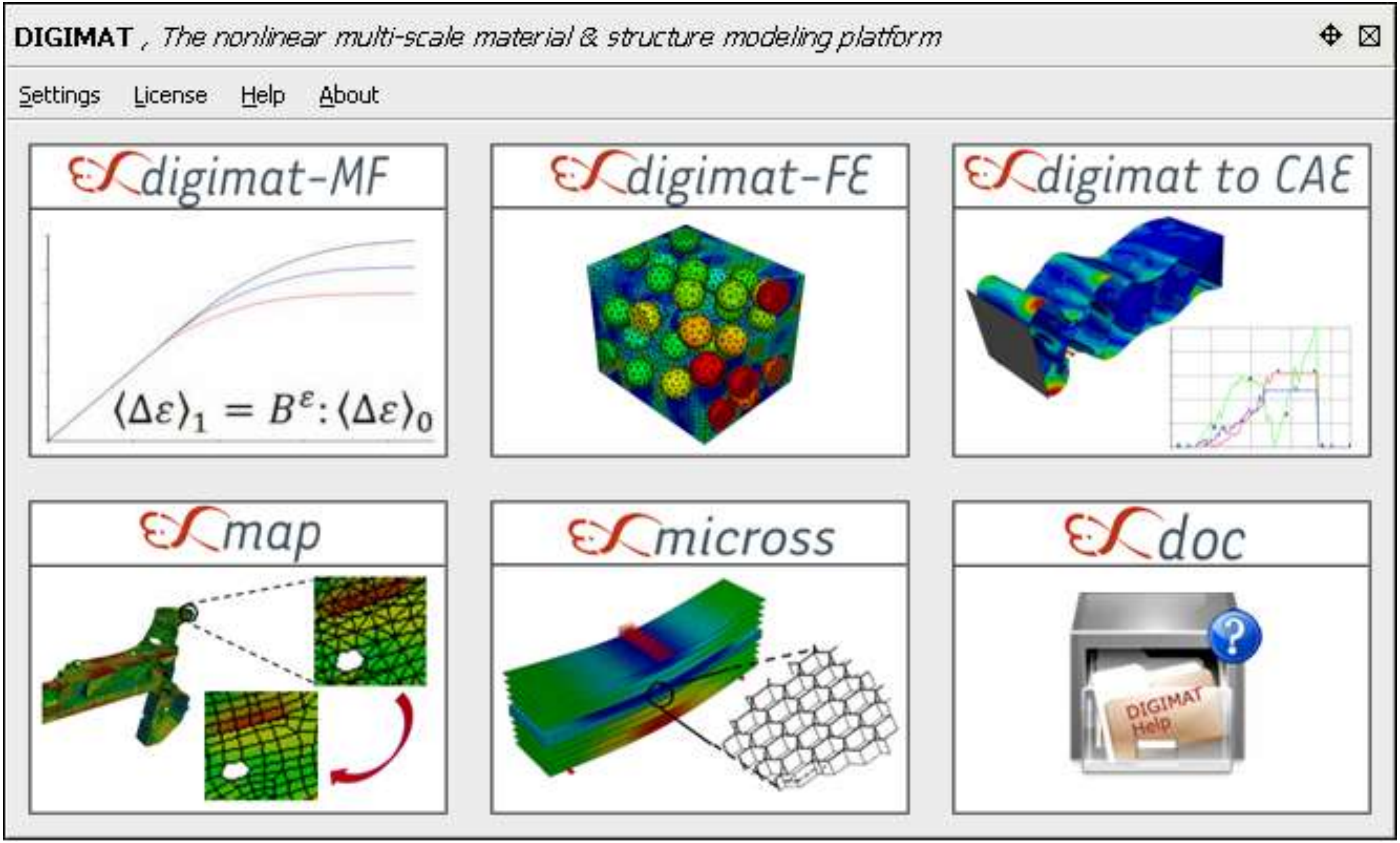




Modeling Needs

- How can we design the optimal material ?
  - ✓ What is the relation between the material microstructure (e.g. Fiber content, length, orientation) and its final properties (e.g. Mechanical, Thermal, Electric,…) ?
- How to select the optimal material and use its anisotropy for optimal structure performance ?
  - ✓ What is the link between the material and structure performance ?
- How can we optimally process the material and structure ?
  - ✓ What is the relation between the process parameters and product performance ?
- How can we achieve these objectives efficiently ?
  - ✓ Predict the composite properties (i.e. Anisotropic, nonlinear, time-dependent, …) as a function of its microstructure.
  - ✓ Predict the product properties as a function the local material microstructure, as induced by the processing conditions (e.g. injection molding, draping,…)

DIGIMAT, *The nonlinear multi-scale material & structure modeling platform*

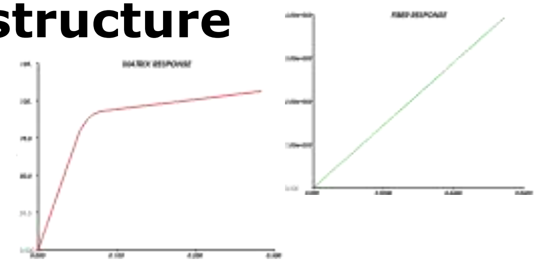


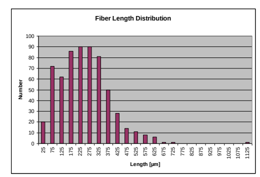
DIGIMAT to CAE, Coupling Injection Molding to Realistic FEA

Process Design → **Material Design** ↔ **Structure Design**

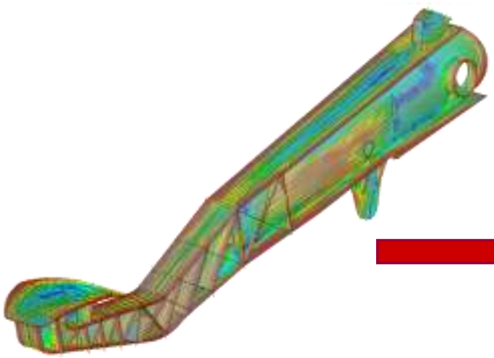
Phase Material & Composite Microstructure

- -Fiber Shape
- -Fiber Weight Fraction
- -Fiber Length Distribution

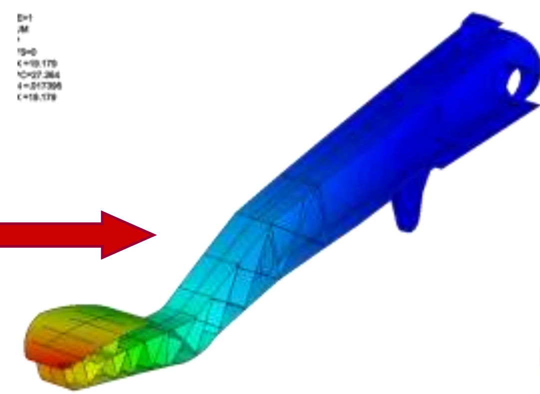




Fiber Orientations



Structural FEA



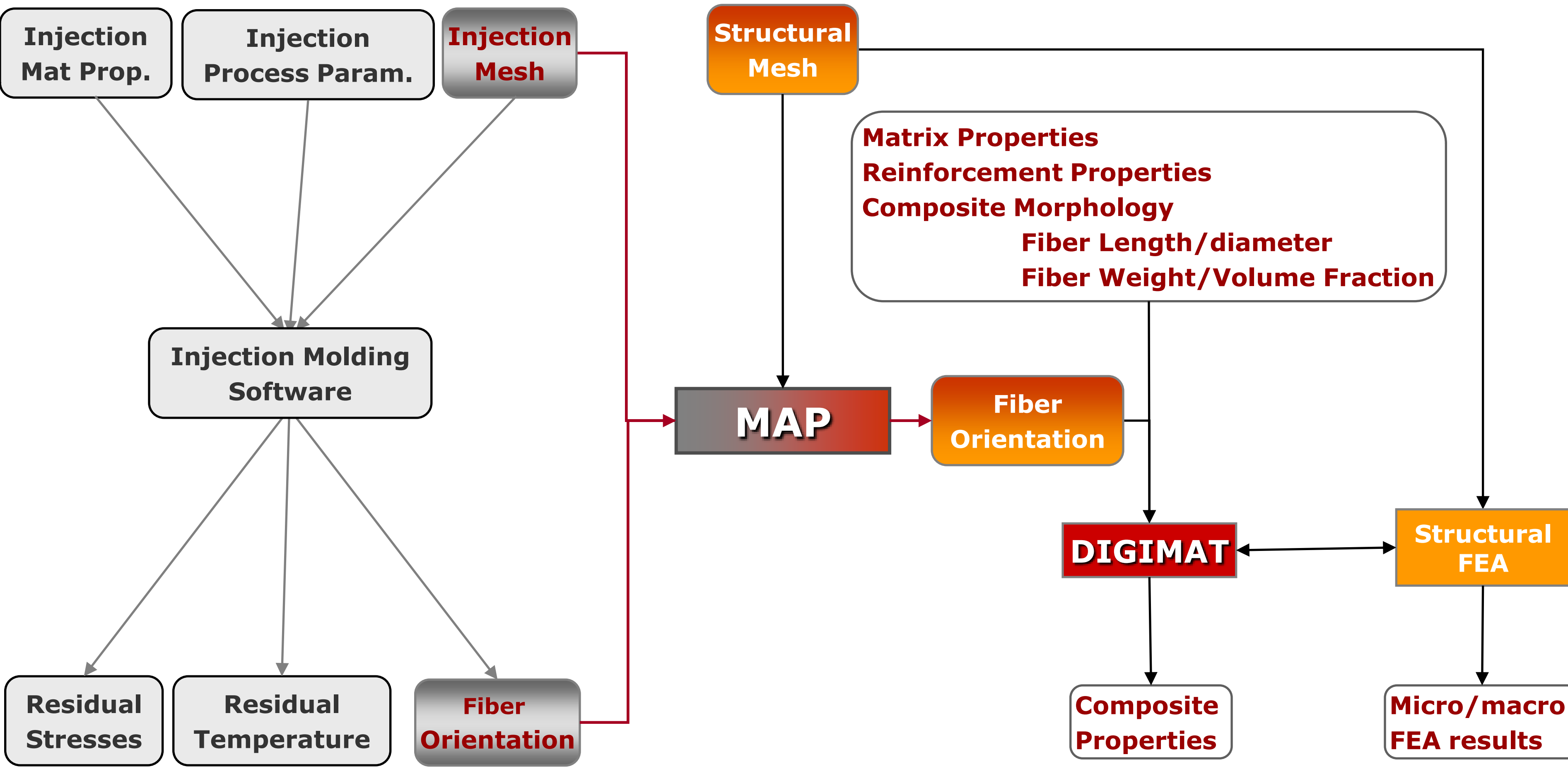
digimat

moldflow
3D-SIGMA
Moldex3D

Abaqus Solution Partner
SIMULIA
LSTC Livermore Software Technology Corp.
Samtech
ANSYS
ESI GROUP THE VIRTUAL TRY-OUT SPACE COMPANY

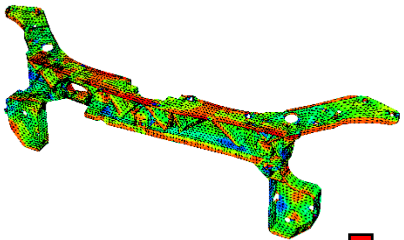
Courtesy of Trelleborg & Rhodia

The Multi-Scale Modeling Approach for Fiber Reinforced Engineering Thermoplastic



Interaction between DIGIMAT and FEA

Classical FE process

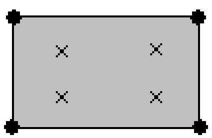


FE model level

Nodal coordinates, …

Internal forces and element stiffness

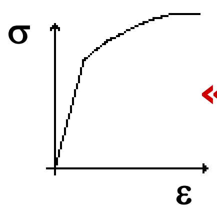
Element level



Strain increments, material state, …

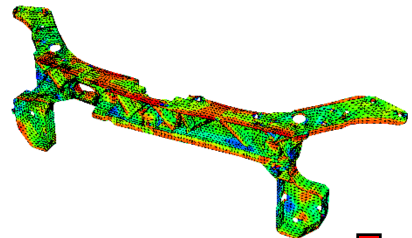
Stresses and material stiffness

Material level



« In code » model

Coupled FE/DIGIMAT process

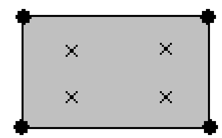


FE model level

Nodal coordinates, …

Internal forces and element stiffness

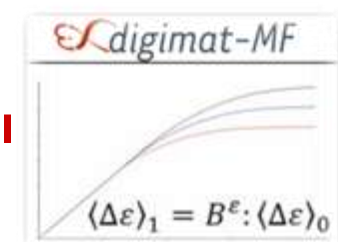
Element level



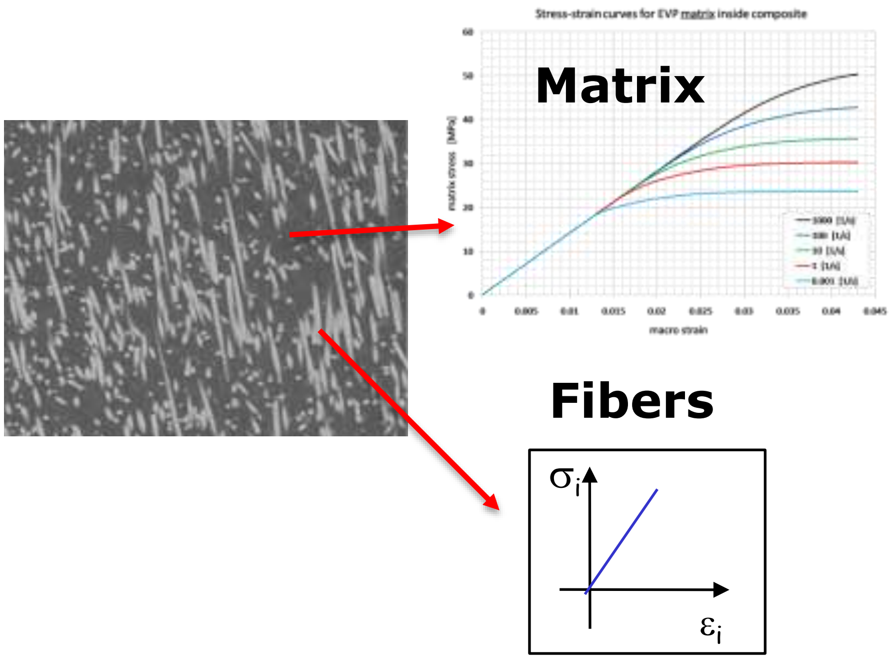
Strain increments, material state, …

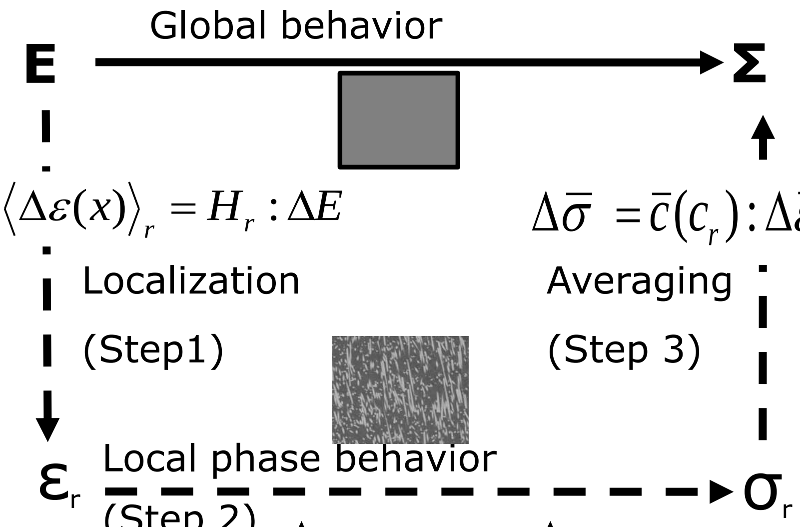
Stresses and material stiffness

Material level



Mean Field Homogenization





$$\Delta\varepsilon_r = \langle \Delta\varepsilon(x) \rangle_r = H_r : \Delta E$$

$$\Delta\bar{\sigma} = \bar{c}(c_r) : \Delta\bar{\varepsilon}$$

$$\Delta\sigma_r = c_r : \Delta\varepsilon_r$$

Composite behavior depends explicitly on the:

- Behavior of each phase
- Inclusion shape (Aspect Ratio)
- Inclusion orientation
- Inclusion evolution (finite strain)

Pros

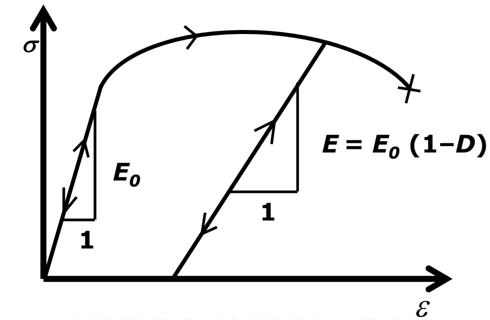
- Fast model preparation/solution
- Accurate predictions
- Enables fully coupled nonlinear multi-scale Analyses

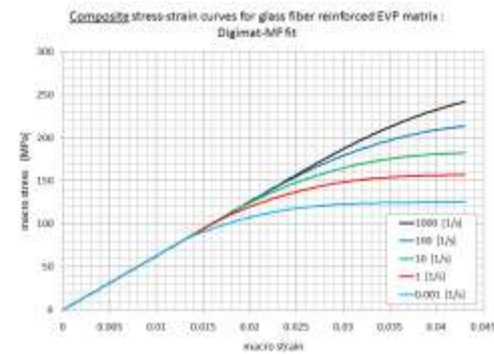
Cons

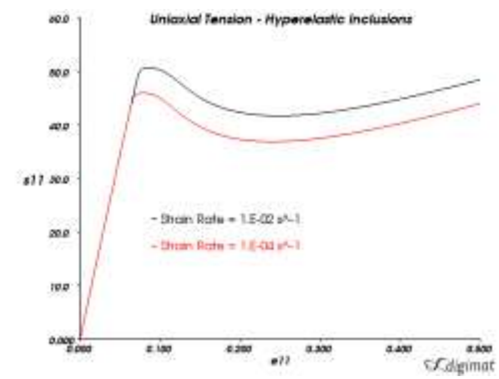
- Ellipsoidal inclusions
- Uniformly distributed inclusions
- Average per phase (micro) results

DIGIMAT-MF: Major Capabilities

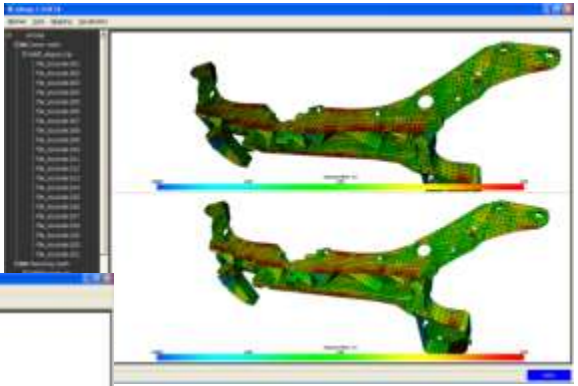
- Materials: Per Phase (of a composite):
  - ✓ **Thermo-Elastic**: Anisotropic, Temperature dependent.
  - ✓ **Elasto-Plastic:** Small deformations/Large rotations
    - Pressure dependent (Drucker-Prager)
    - **Continous Damage** (4 parameters model)
  - ✓ **Visco-elastic:** Linear, small deformations/Large rotations
  - ✓ **Elasto-Viscoplastic:** Large deformations.
  - ✓ **Hyperelastic** (5 models): Large deformations
- Micro-structure:
  - ✓ **N-Phase** (e.g. fibers + mineral inclusions, distribution of fiber "lengths")
  - ✓ **General Orientation** (e.g. Orientation Tensor from MOLDFLOW)
  - ✓ **Inclusion Coating** (i.e. Fiber/Matrix Interface)
  - ✓ **Voids**
- **Micro** & Macro **Failure** Indicators
- 1^{st} & 2^{nd} Order Incremental Homogenization Methods:
  - ✓ Mori-Tanaka
  - ✓ Interpolative Double Inclusion (High Concentrations/Contrast)
- **Thermo-Mechanical Static & Dynamic** (Impact) Loading
- **Nonlinear**, **strongly coupled** CAE Interfaces

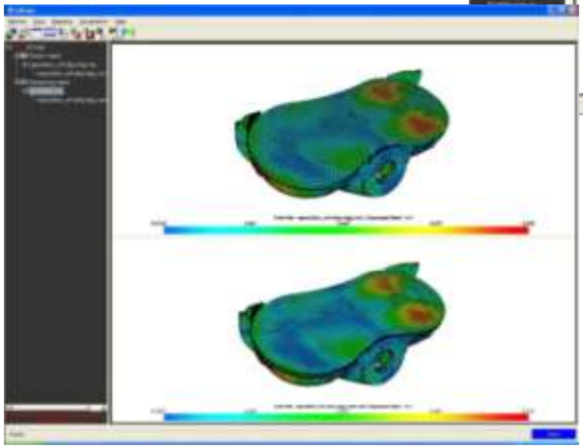


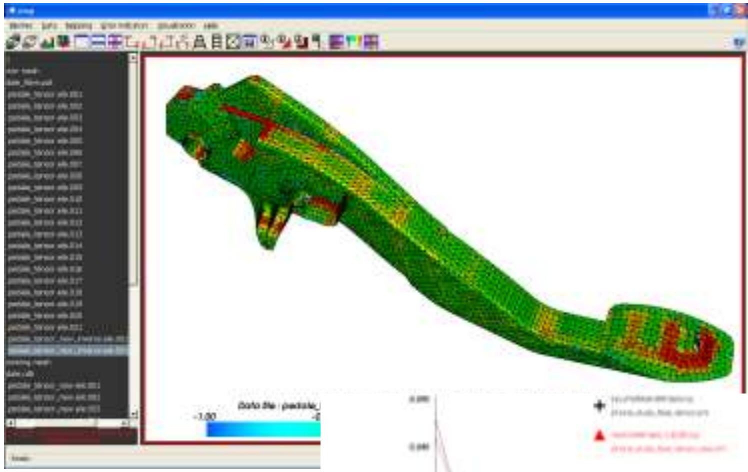


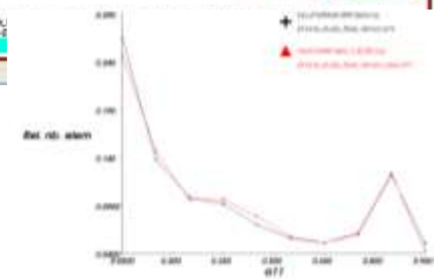


MAP: 2D & 3D mapping









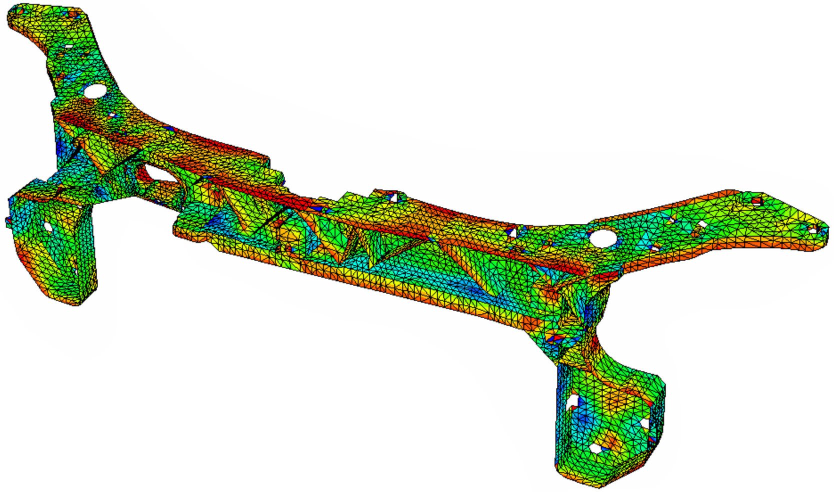
- Mesh Types
  - ✓ Mid-plane(Triangles)→Shell (Triangle or Quad)
  - ✓ 3D (Tet) → 3D (Tet or Hex)
- Mesh Format
  - ✓ Abaqus
  - ✓ ANSYS
  - ✓ LS-DYNA
  - ✓ PAM-CRASH
- Mapped Data:
  - ✓ fiber Orientation
  - ✓ Initial Stresses
  - ✓ Initial Temperature
- Mapping Error Indicators
  - ✓ Global (Contour plot)
  - ✓ Local (Histogramme)
- Model Scaling/Positioning
- Data post-processing
  - ✓ Synchronized
  - ✓ Contour or vector plots

SOME APPLICATIONS

FAT B85 : FE & Material Models (PP-LGF)

DIGIMAT Material Model

- ✓ PP-Matrix :
  - E= 1500 MPa
  - ν = 0.3
- ✓ Fibres :
  - E = 72000 MPa
  - ν = 0.22
  - Volume Fraction = 19.46 % (40 % Weight Fraction)
  - Aspect ratio : 100 (Long Fibers)
  - Orientation : MOLDFLOW 5.1

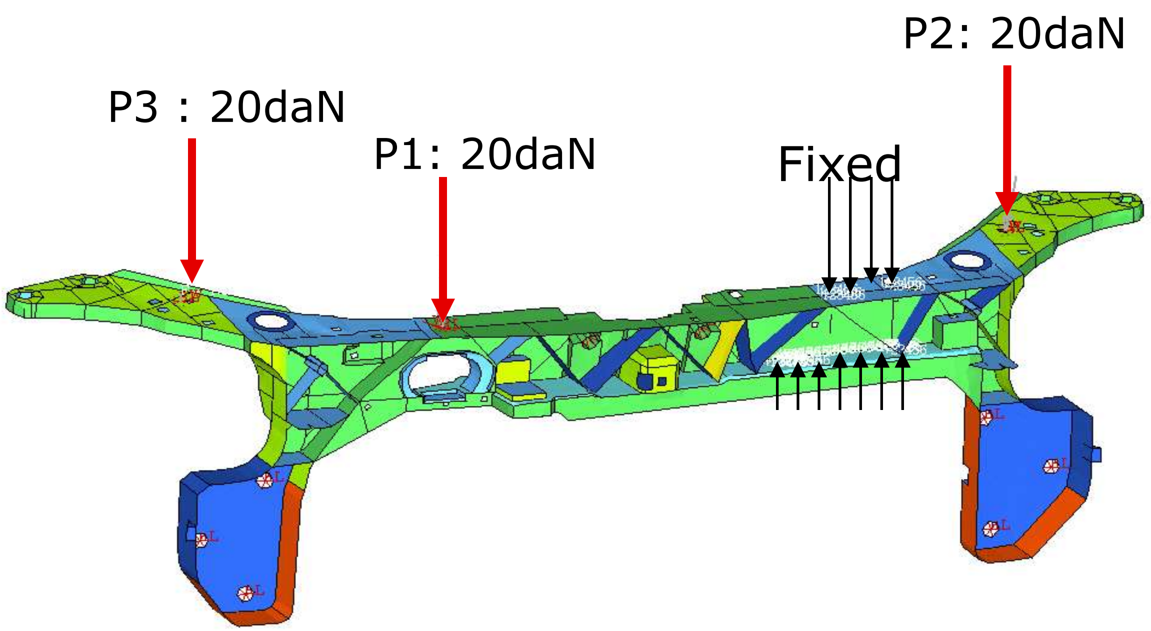


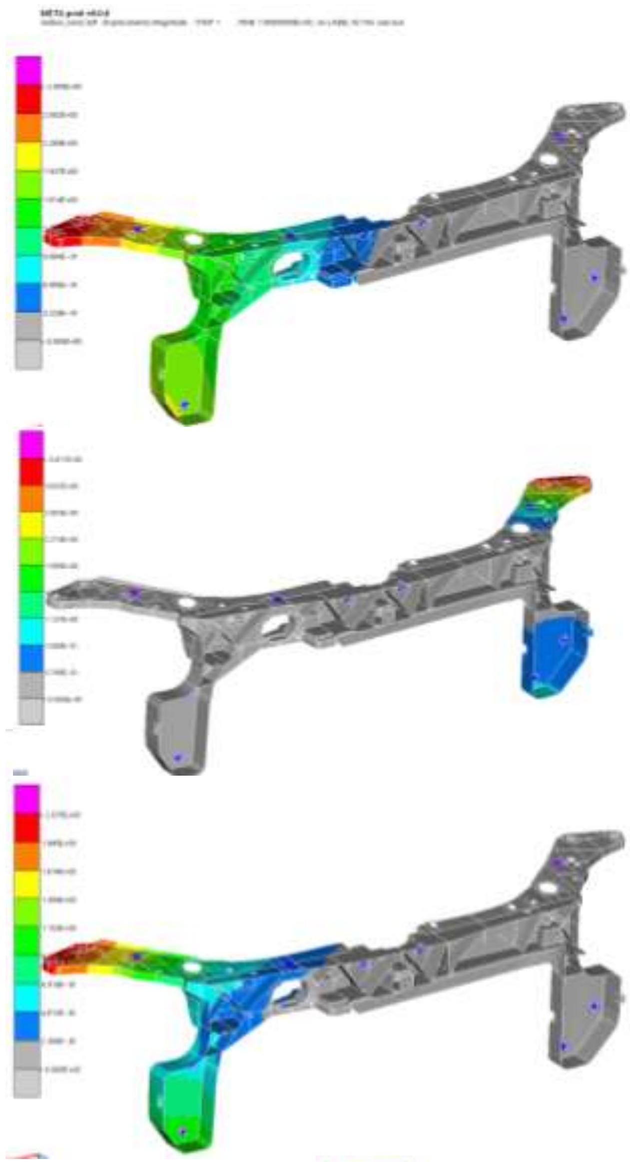
ABAQUS FEA Model

- ✓ # Elements =12632 (S3R)
- ✓ # Nodes = 6365
- ✓ # DOF = 38190
- ✓ Material : PP-LGF with DIGIMAT 1.6
- ✓ Initial Stresses: MOLDFLOW 5.1

Courtesy of: RENAULT

FAT B85: Structural Stiffness



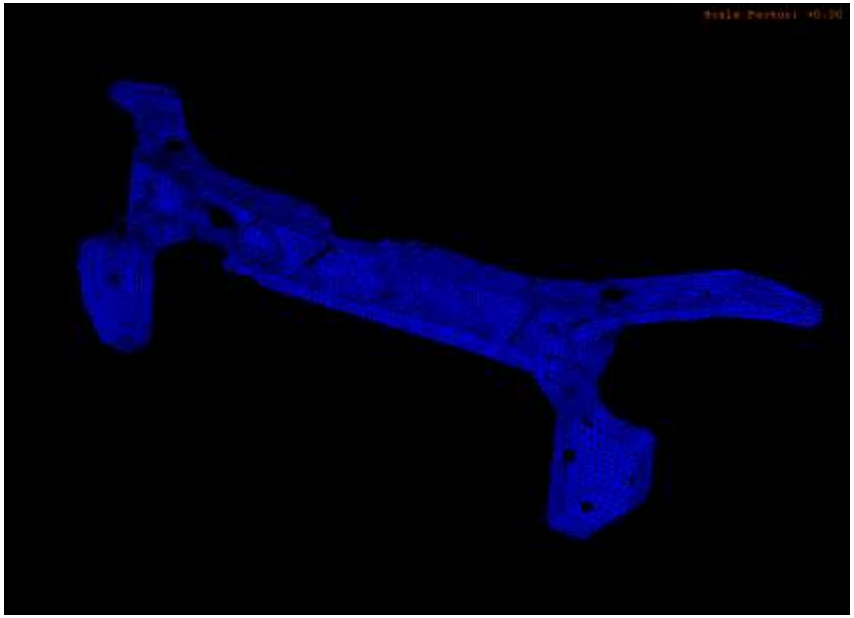


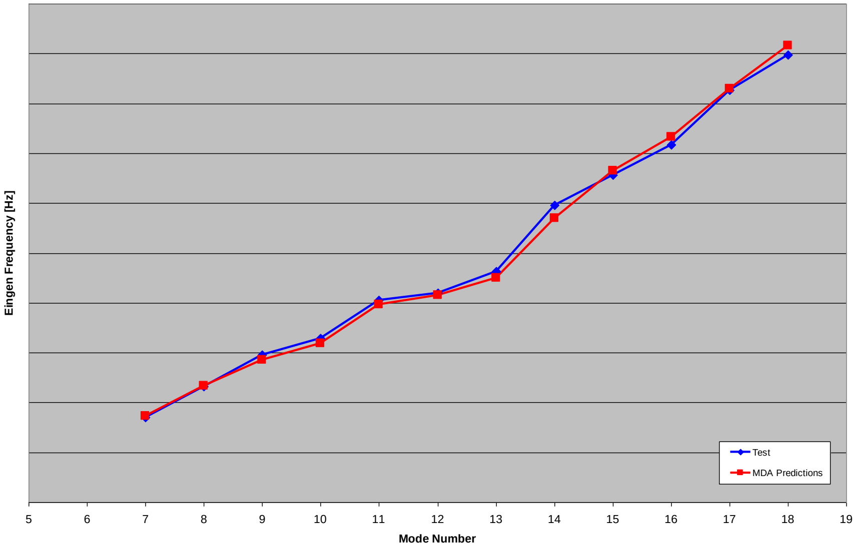
Structural Stiffness	(MDA-Test)/Test
P1	-3.75%
P2	+8.07%
P3	-6.97%

Courtesy of: RENAULT

FAT B85: Modal Response

Eigen Freq.	(MDA-Test)/Test
7	1.68%
8	0.96%
9	-3.66%
10	-2.76%
11	-1.84%
12	-1.06%
13	-2.83%
14	**-4.45%**
15	1.46%
16	2.09%
17	**0.47%**
18	2.21%



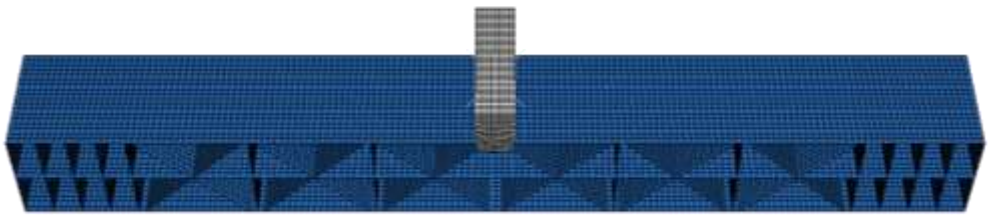


Courtesy of: RENAULT

3-Point Bending Beam: Problem Definition

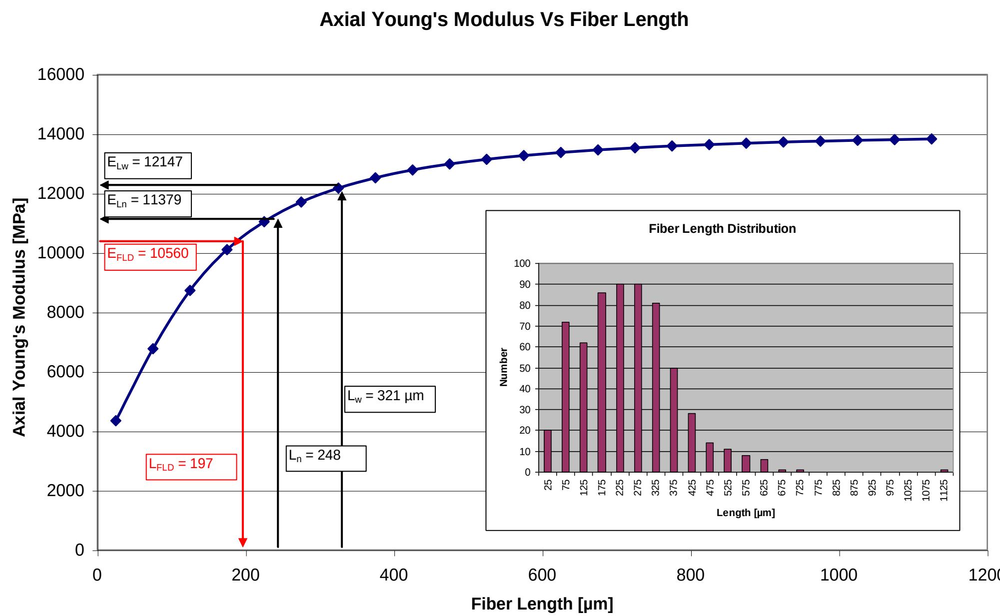
ABAQUS FE Model

- ✓ Number of Elements=30,532
- ✓ Number of Nodes= 31,528
- ✓ Number of DOF=154,089



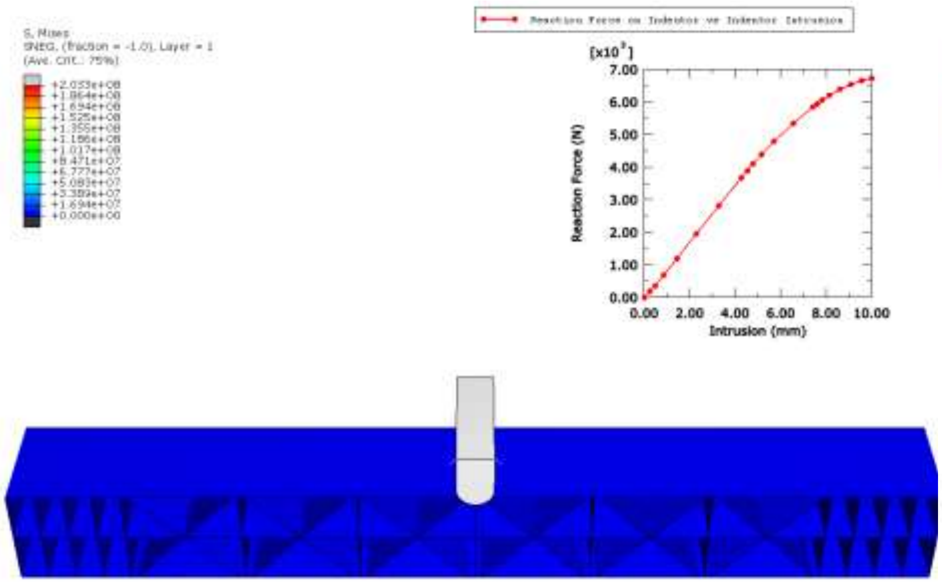
Material : PA 35% GF

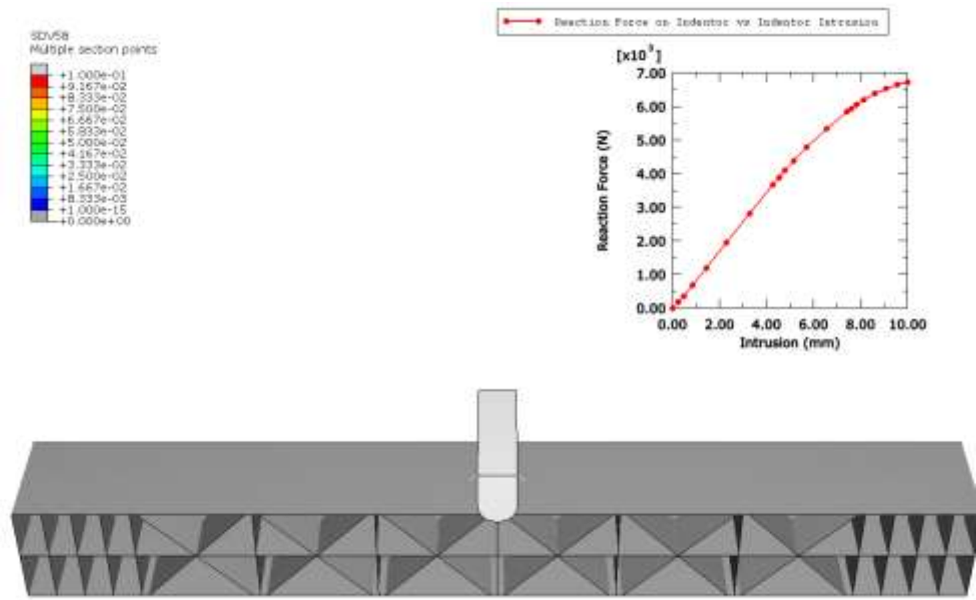
- ✓ **Matrix :**
  - Young's modulus: 2.75 E+09 Pa
  - Poisson ratio : 0.37
  - yield_stress = 4.0e+07 Pa
  - hardening_model = exponential linear
  - hardening_modulus = 3.67e+07
  - hardening_exponent = 3.2e+02
  - hardening_modulus2 = 3.0e+07
  - Density: 1.13 E+03 Kg/m^3
- ✓ **Fibers :**
  - Young's modulus: 7.2e+10 Pa
  - Poisson ratio: 0.22
  - Density:2.47e+03 Kg/m^3
  - Weight fraction : 35 %
  - Aspect ratio :
    - 25
    - *Fiber length Distribution*
  - Fiber Orientation
    - Moldflow (DSM)



Courtesy of: **DSM**

3-Point Bending Beam



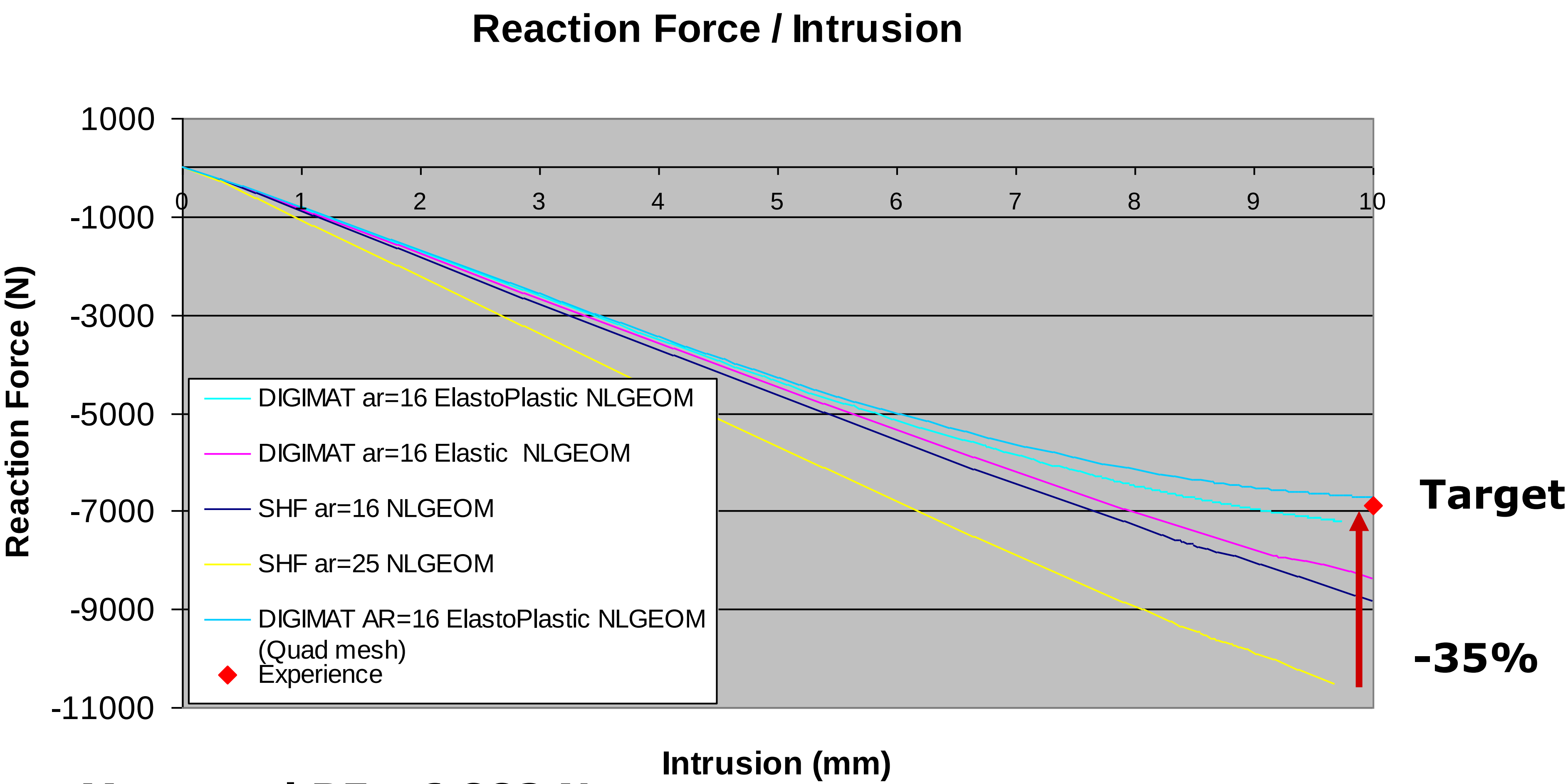


von Mises Stresses
In PAGF

Accumulated Plastic Strain
In PA matrix

Courtesy of: **DSM**

3-Point Bending Beam: F/d Curves



Measured RF= 6,883 N

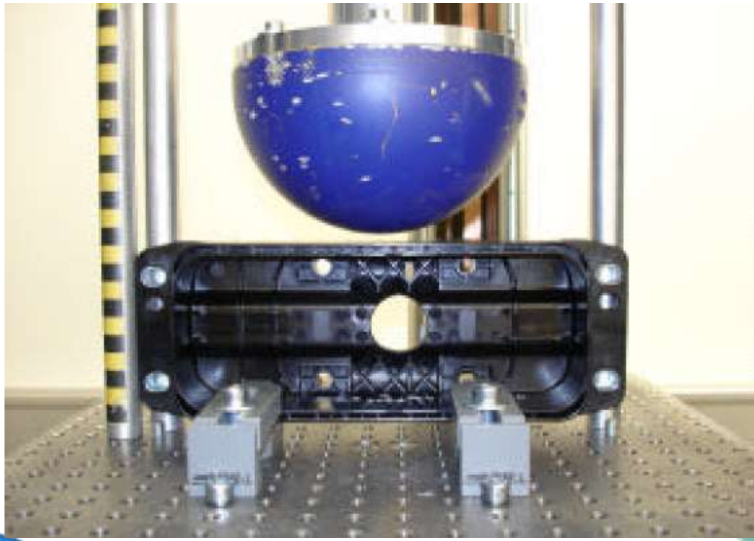
Predicted RF (Tri mesh) = 7,170 N (+4%)

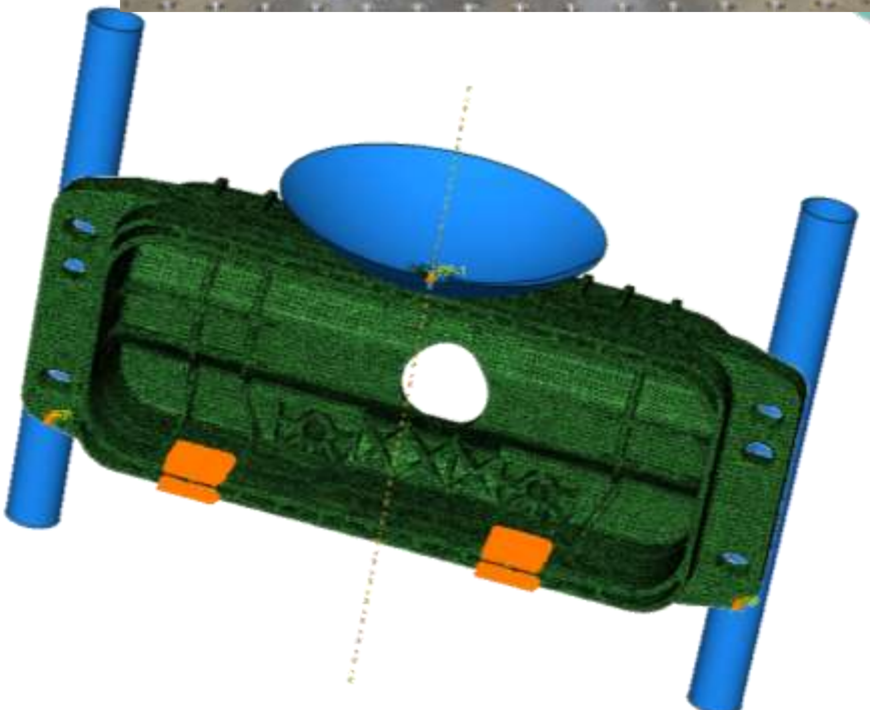
Predicted RF (Quad mesh) = 6720 N (-2.4%)

Courtesy of: **DSM**

Multi-Scale Modeling of Passenger Airbag Container

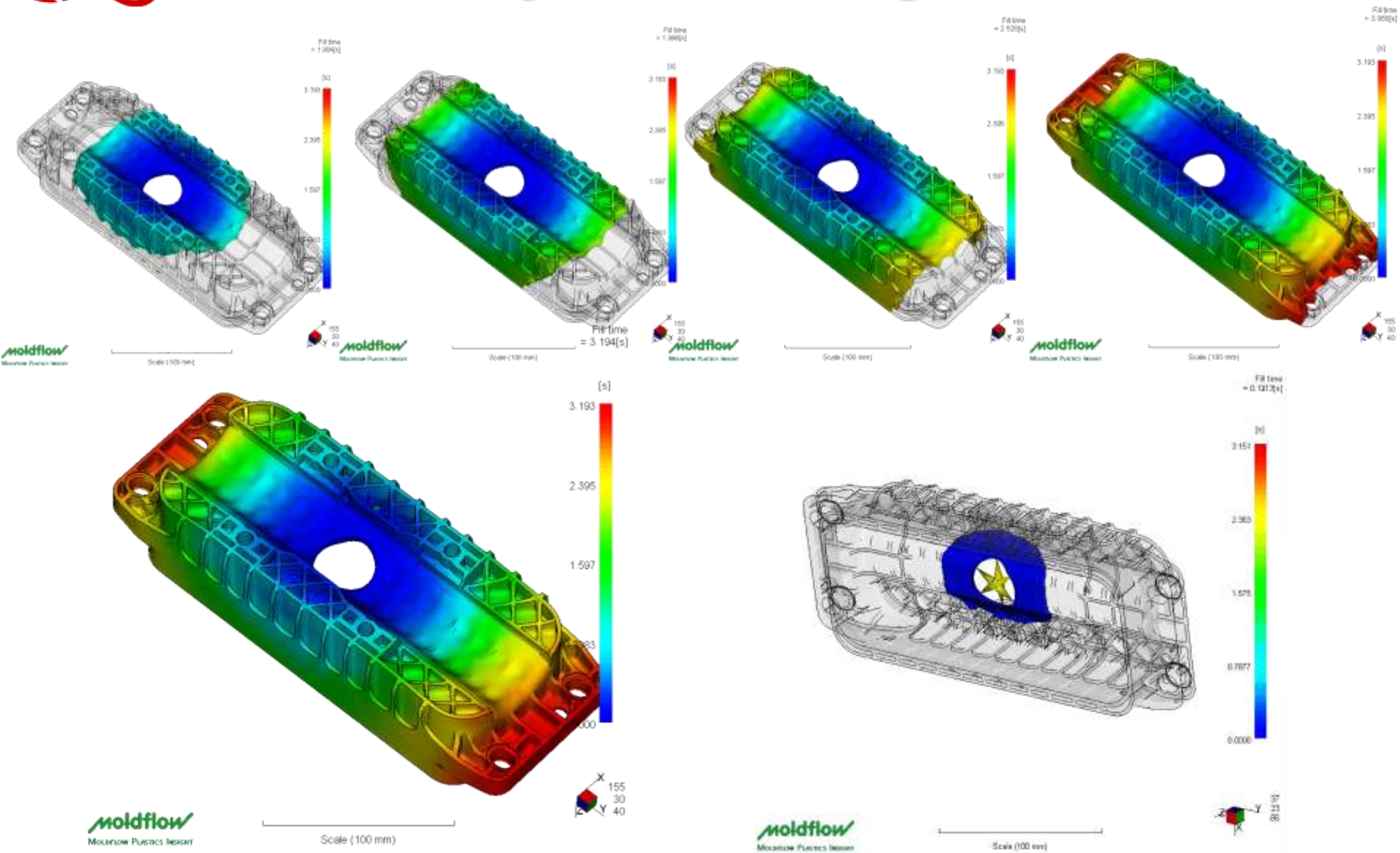
- Moldflow's Injection Molding Mesh:
  - ✓ Number of nodes: 584,123
  - ✓ Number of elements: 3,369,976
  - ✓ Element type: C3D4
- Abaqus Structural Mesh:
  - ✓ Number of nodes: 368,852
  - ✓ Number of elements: 194,794
  - ✓ Element type: C3D10, C3D10M
- Material: AKULON K224-PG8 (40% Glass filled Impact Modied Polyamide)
  - ✓ Matrix: Impact Modified Polyamide
    - type = elastoplastic
    - Young Modulus = 2350 MPa
    - Poisson Ratio = 0.38
    - Yield stress =30 MPa
  - ✓ Fibers: E-Glass
    - Type = elastic
    - Density = 2.54 E+3
    - Young Modulus = 72 000 MPa
    - Poisson Ratio = 0.22
    - Weight fraction = 40%
    - Aspect ratio (L/D) = 20
    - Orientation = Moldflow3D (.xml)





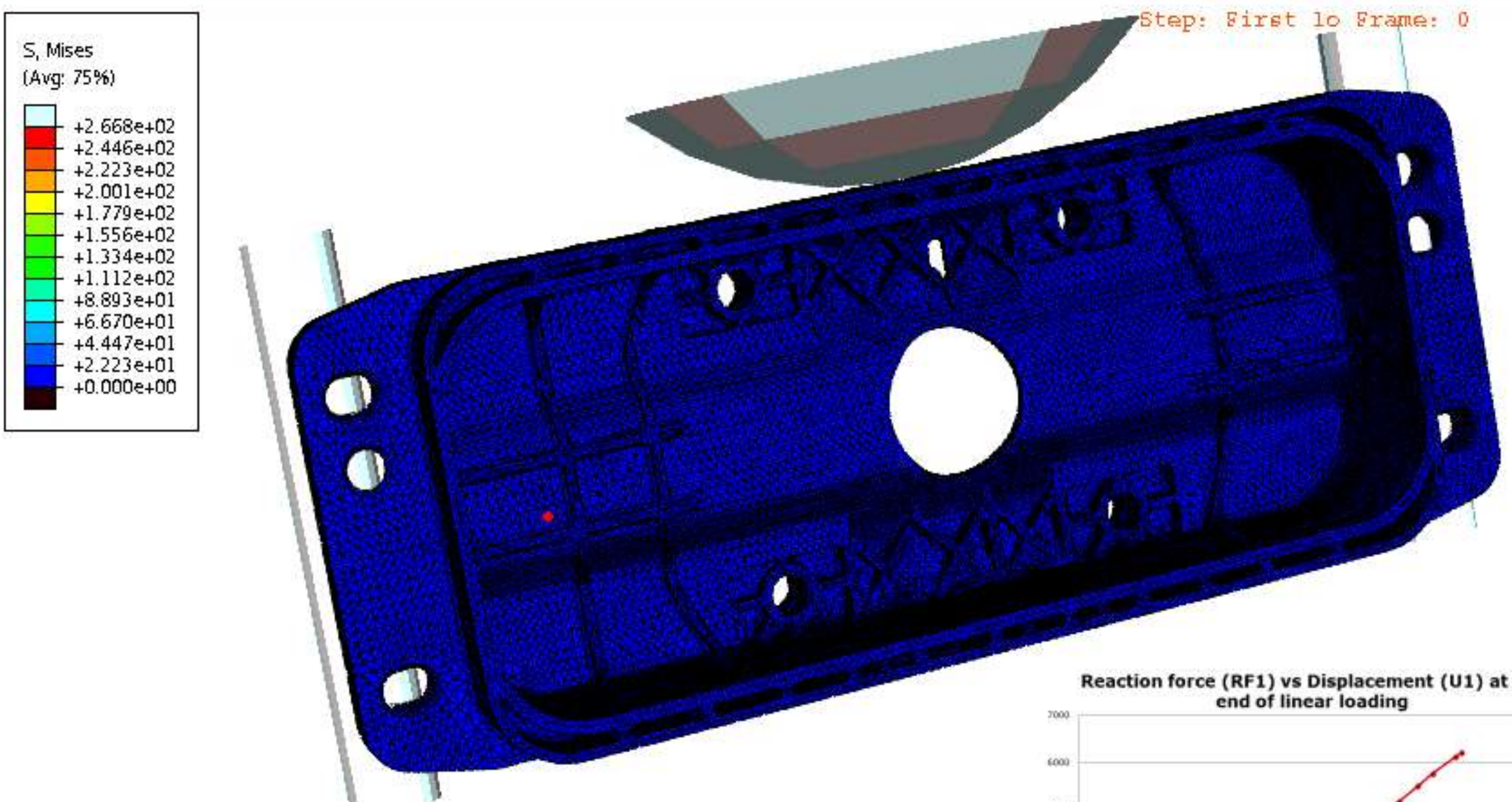
Courtesy of: AUTOLIV & DSM

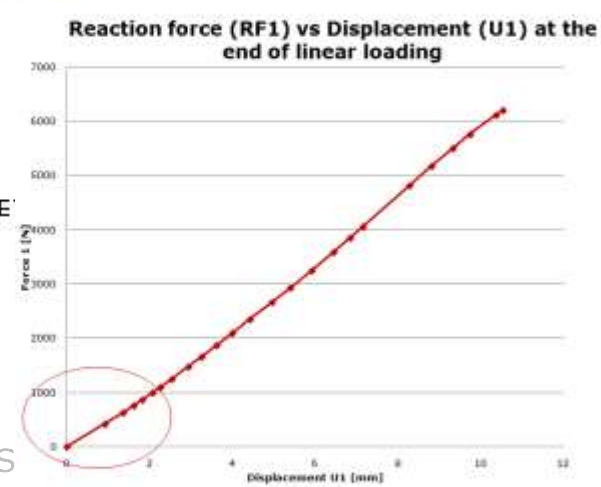
Moldflow Injection Molding Simulation



Courtesy of: AUTOLIV & DSM

Quasi-Static/Monotonic: Elasto-Plastic DIGIMAT Material





Courtesy of: AUTOLIV & DSM

DIGIMAT to Abaqus Nonlinear Multi-Scale Analyses: Results & CPU

RF @ Imposed D	Experimental Force	DIGIMAT to Abaqus	Difference
Linear (to 10.5mm)	~ 6477 N	6203.49 N	-4.2%
Cyclic (to 7mm)	~ 4765N	3949.18 N	-17 %

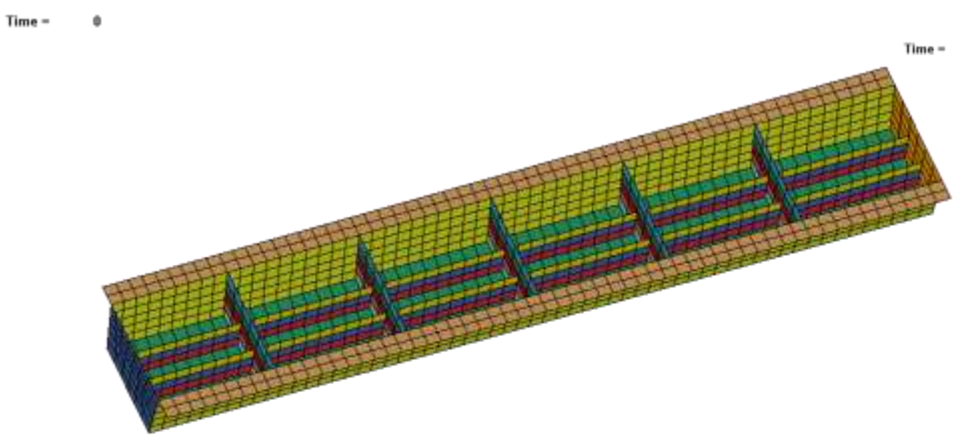
Loadings	Linear	Cyclic
CPU Time	82 h 05 m	41 h 13 m
Elapsed time	25 h	56 h 28 m
# CPUs (Opteron 64 bits)	4	1

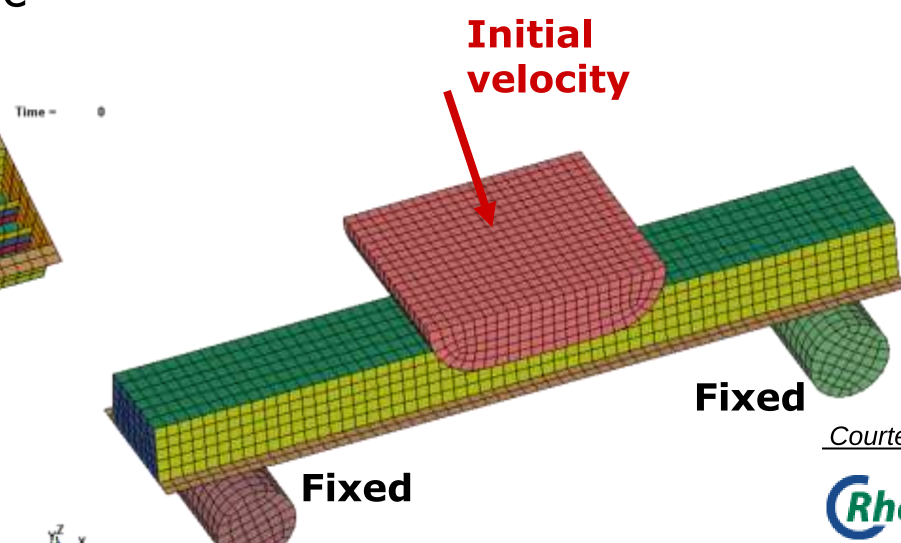
Courtesy of: AUTOLIV & DSM

Multi-Scale Impact & Failure Simulation

- LS-DYNA FE Mesh
  - ✓ 3,630 Elements
  - ✓ 3,646 Nodes
  - ✓ 16 composite shell sections with different thicknesses.
  - ✓ 5 integration points across the thickness
  - ✓ Characteristic dimension : 400x50x30 mm.

- Loading & BC :
  - ✓ Simply supported beam
  - ✓ Initial velocity: V_0 =-5 m/sec

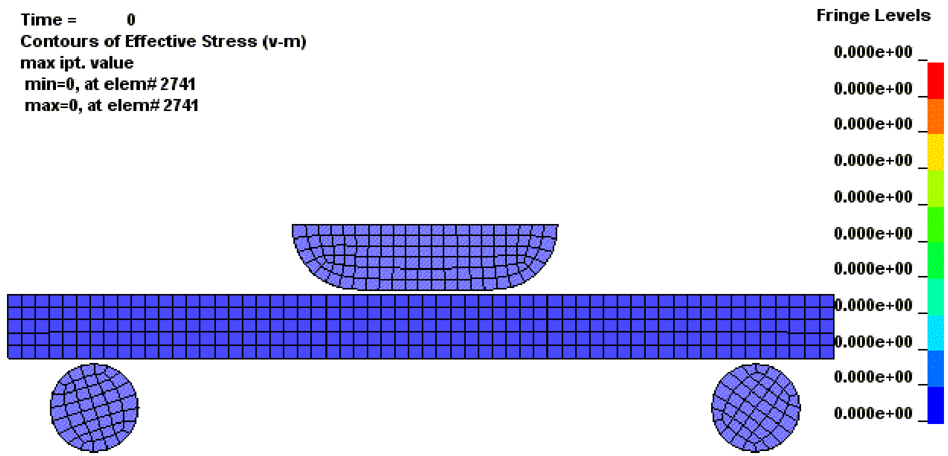


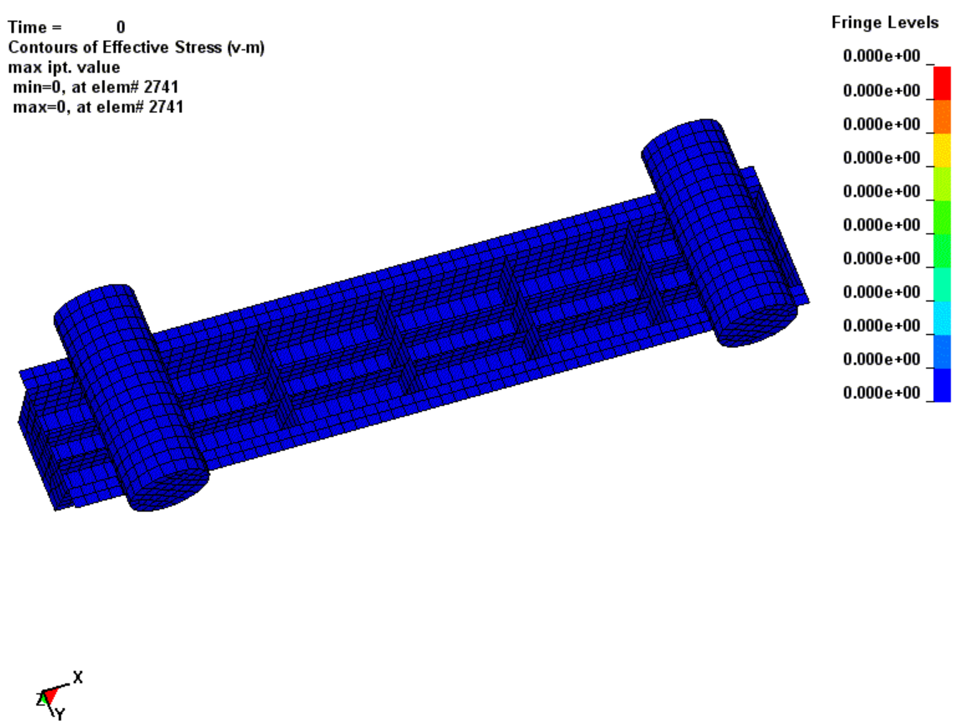


Courtesy of :

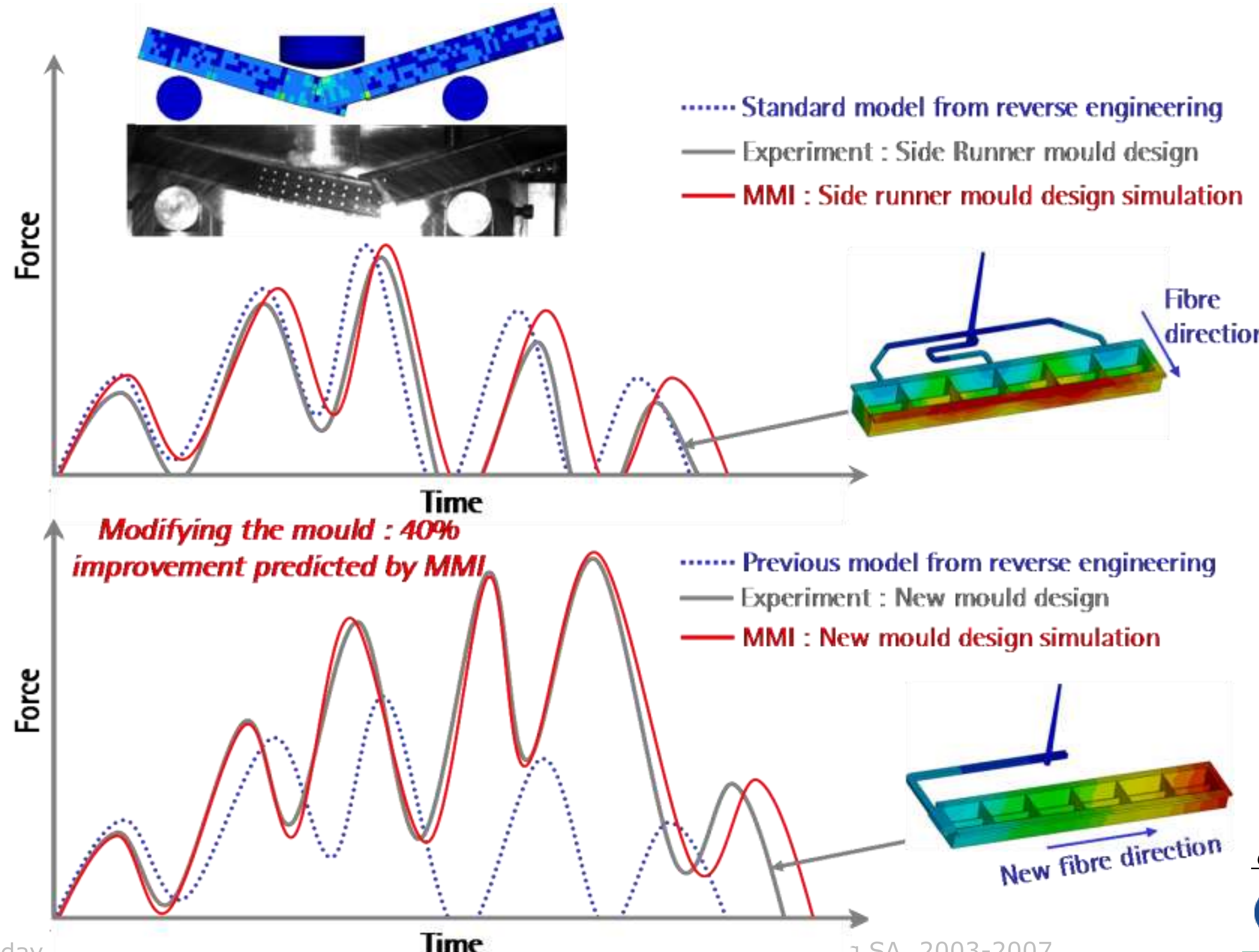
Rhodia

Impact & Failure Analysis: Aligned Fibers



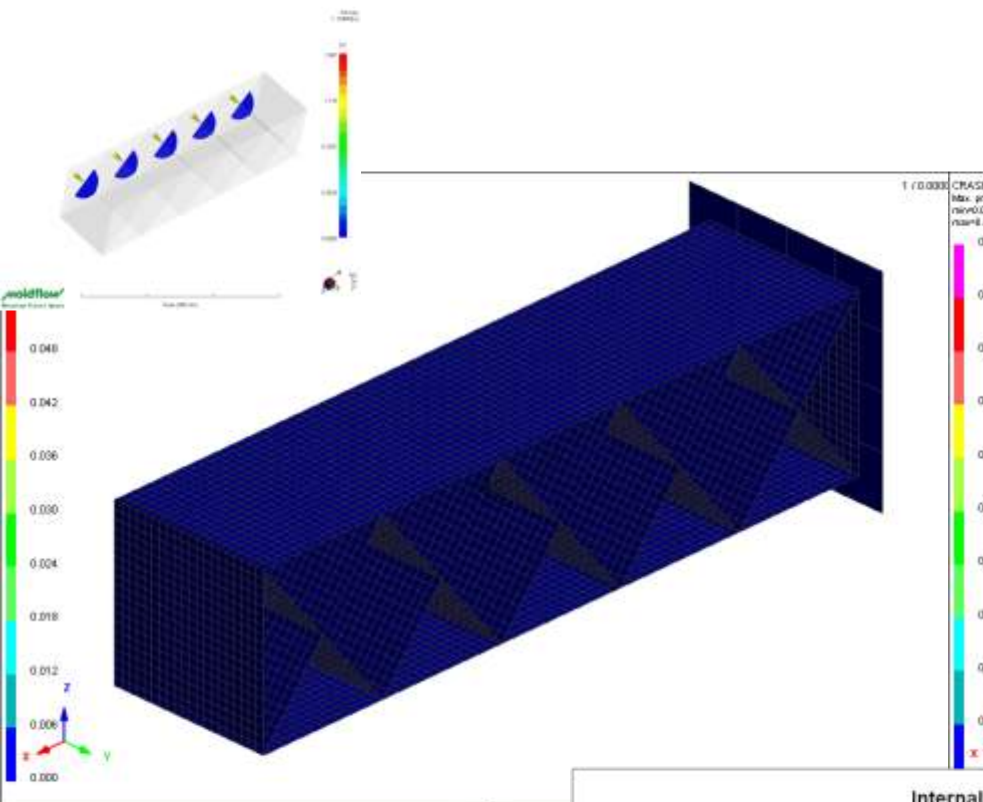


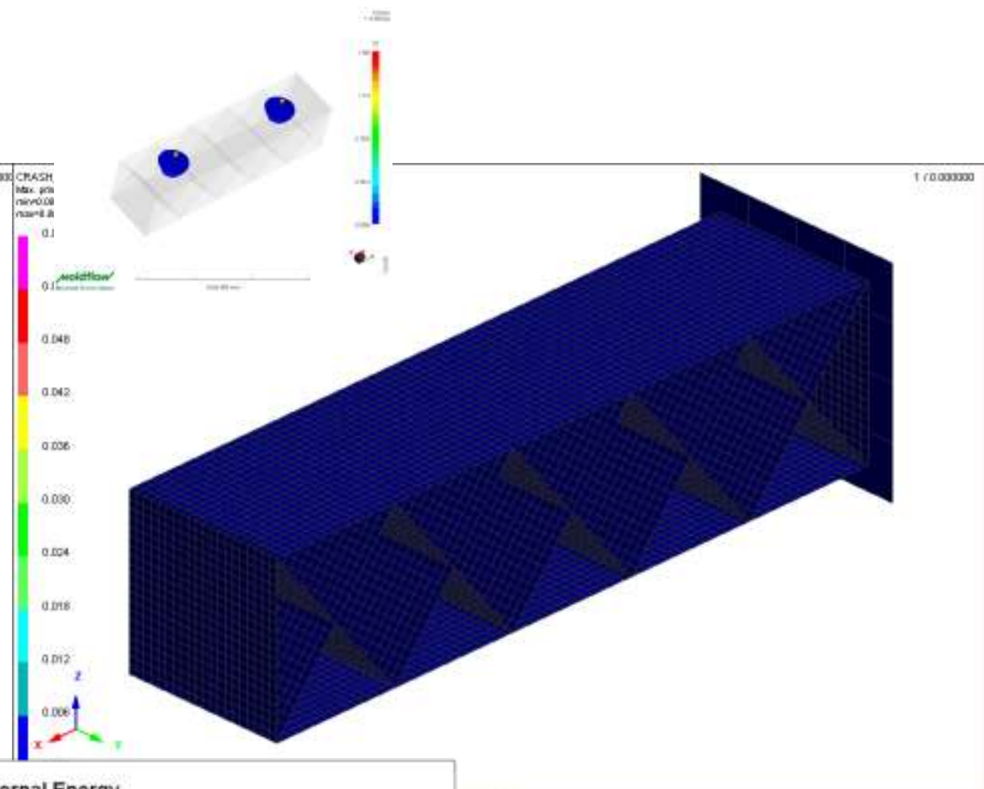
Failure Prediction: Effect of Injection Gate Location

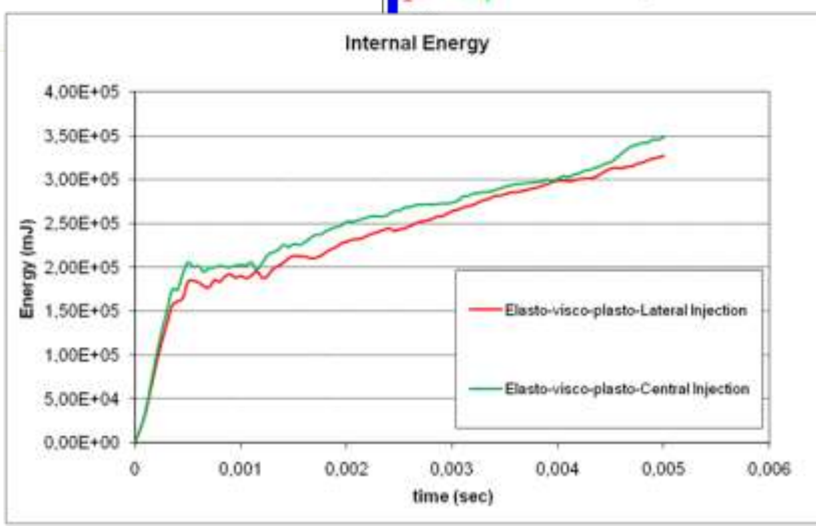


Courtesy of : Rhodia

DIGIMAT to PAM/CRASH: Impact & Failure







Conclusions

- Mean Field homogenization is a powerful technology to predict the anisotropic, nonlinear and rate-dependent behavior of mutli-phase materials in general and of reinforced plastics in particular.
- Fully coupled multi-scale modeling bridges the gap between the manufacturing process and the final part performance via the material microstructure.
- DIGIMAT offer the tools and modeling process for the optimal and predictive design of reinforced plastic parts.