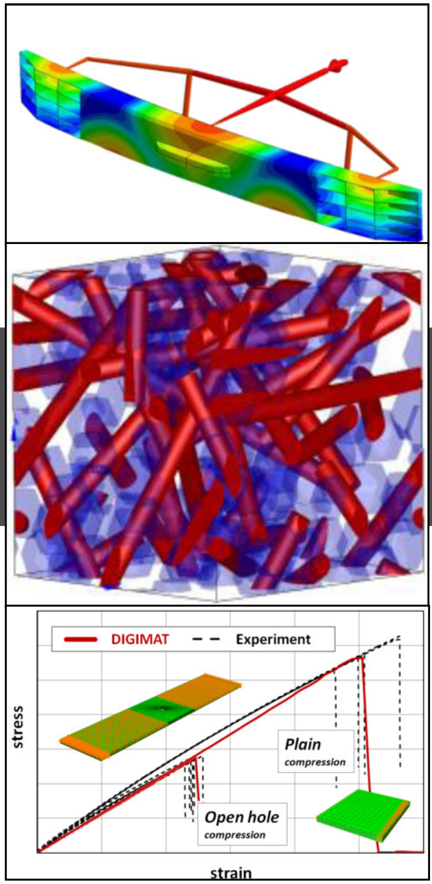


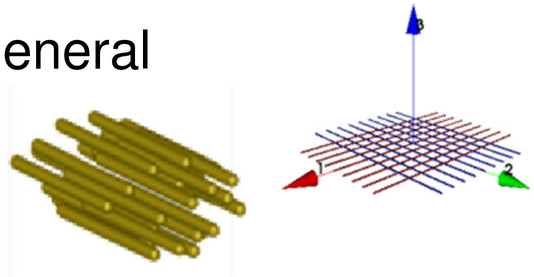
About the Coupling of DIGIMAT to LS-DYNA – a Micro- / Macro Interface for Composite Materials

Christian Liebold
DYNAmore GmbH

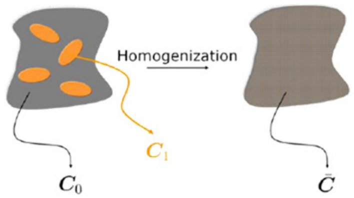
Dr. Jan Seyfarth
e-Xstream

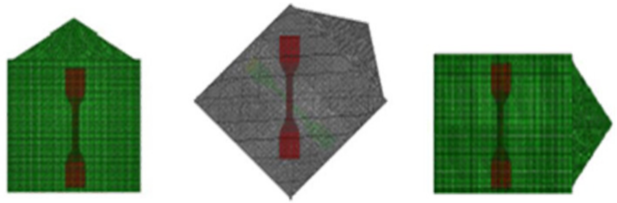
Overview

- Composites in general

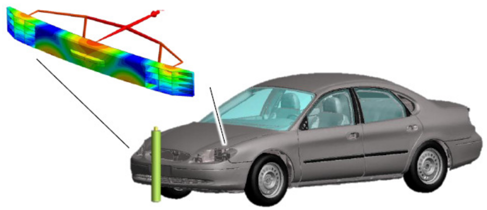


- The DIGIMAT approach – Micro-/Macro Coupling





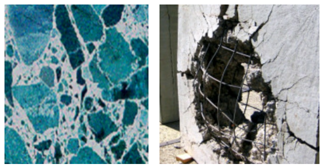
- DIGIMAT – Tools and Applications



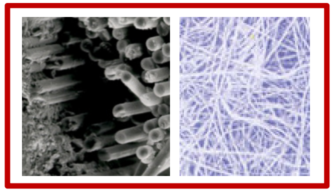
- Conclusion

Composites

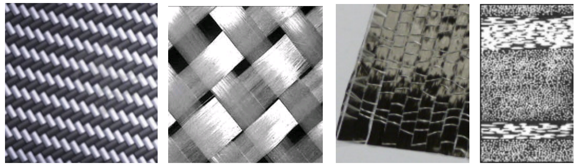
Definition: **Composite materials**, often shortened to composites or called composition materials, are **engineered** or **naturally** occurring materials made from **two or more constituent materials with significantly different physical or chemical properties** which remain separate and distinct within the finished structure.



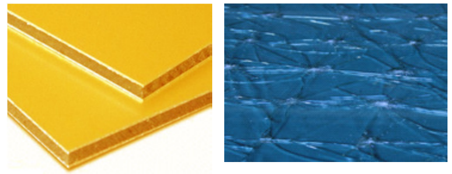
Concrete
(cement/stone/steel)



Short fiber
reinforced polymers
(glass/PP)



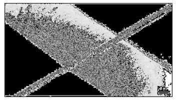
Long fiber
reinforced polymers
(glass/carbon/PA/PP/EP)



Sandwich/Laminates
(alloy/polymer/..glass/PVB/…)

Composites

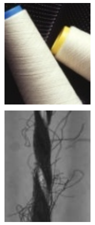
Fibers



[2]

- glass fibers
- carbon fibers
- aramid fibers
- …
- PBO-fiber
- PE-fiber
- natural fibers

Fiber-preforms

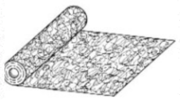


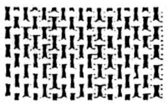
[2]

- filament
- strand
- thread
- ply yarn
- roving

Textile-preforms

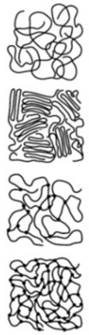
- woven fabric
- thin ply woven fabric
- non-woven fabric
- non crimp fabric
- knit, braid, mat
- stitching
- tailored-fiber placement



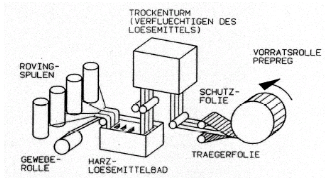


Matrix (Resin)

- Duroplastic resins
- Thermoplastic resins
- Elastomeric resins
- Fillers



[1]



Fiber-Matrix preforms

- short fiber: l ~ 0,1 – 1 mm
- long fiber: l ~ 1 – 50 mm
- endless fiber: l > 50 mm; l/d ->∞ [1]

Duroplastic resin

Thermoplastic resin

long fibers:

- SMC:
  Sheet Moulding Compound
- BMC:
  Bulk Moulding Compound

endless fibers:

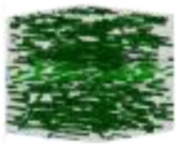
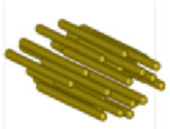
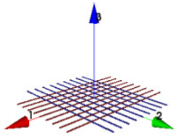
- prepreg

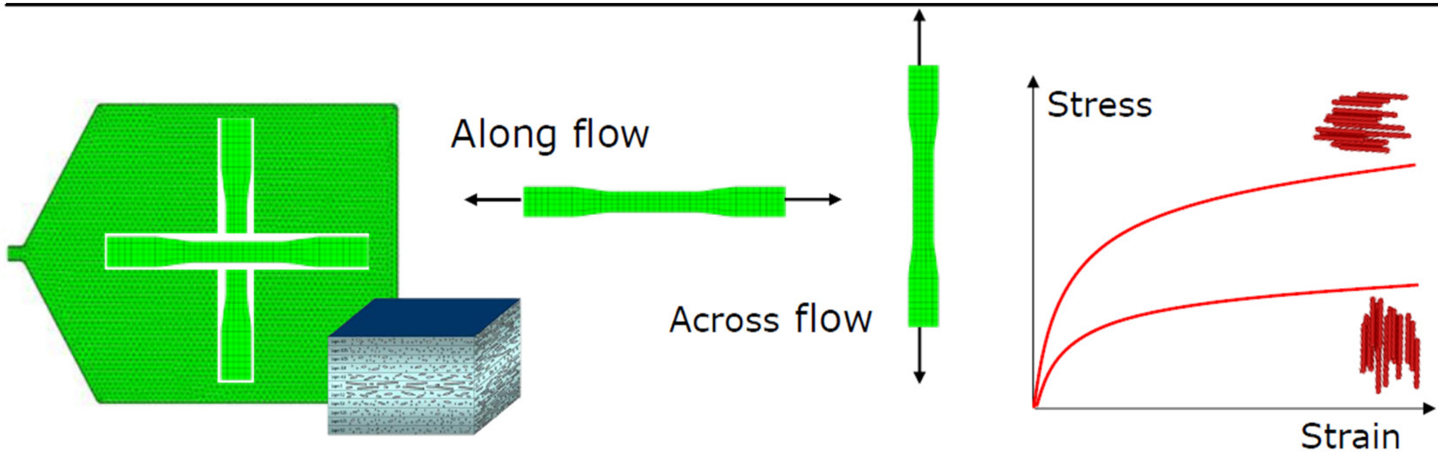
long fibers:

- GMT:
  glass mat reinforced thermoplastic
- LFT:
  long fiber reinforced thermoplastic

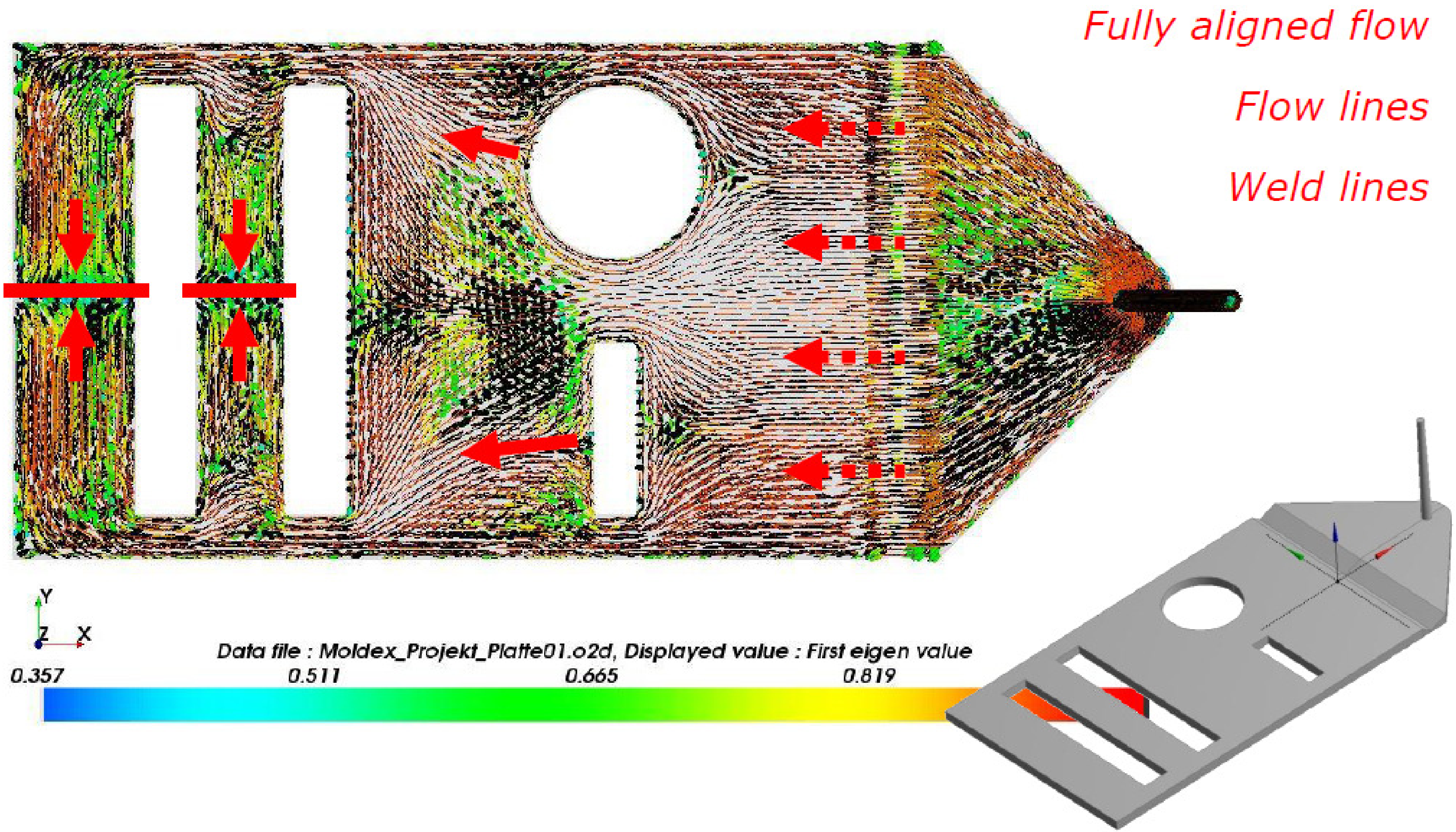
[1] Schuermann: Konstruieren mit Faser-Kunststoff-Verbunden
[2] Wikipedia

Composites

	MATERIALS		MICROSTRUCTURE			PROCESSING
	Matrix	Fibers	Inclusion	Orientation	Setup	Technology
Short fibers 	Thermoplast	Glass (Carbon)	Straight	Random	Skin/core	Injection molding
Long Fibers 	Thermoplast Thermoset	Glass Natural	Straight Wavy	Random Bundling	Complex Layers	Injection molding Compression molding
Continuous Fibers 	Thermoset (Thermoplast)	Glass Carbon	Straight	Fixed	Stacked	Draping

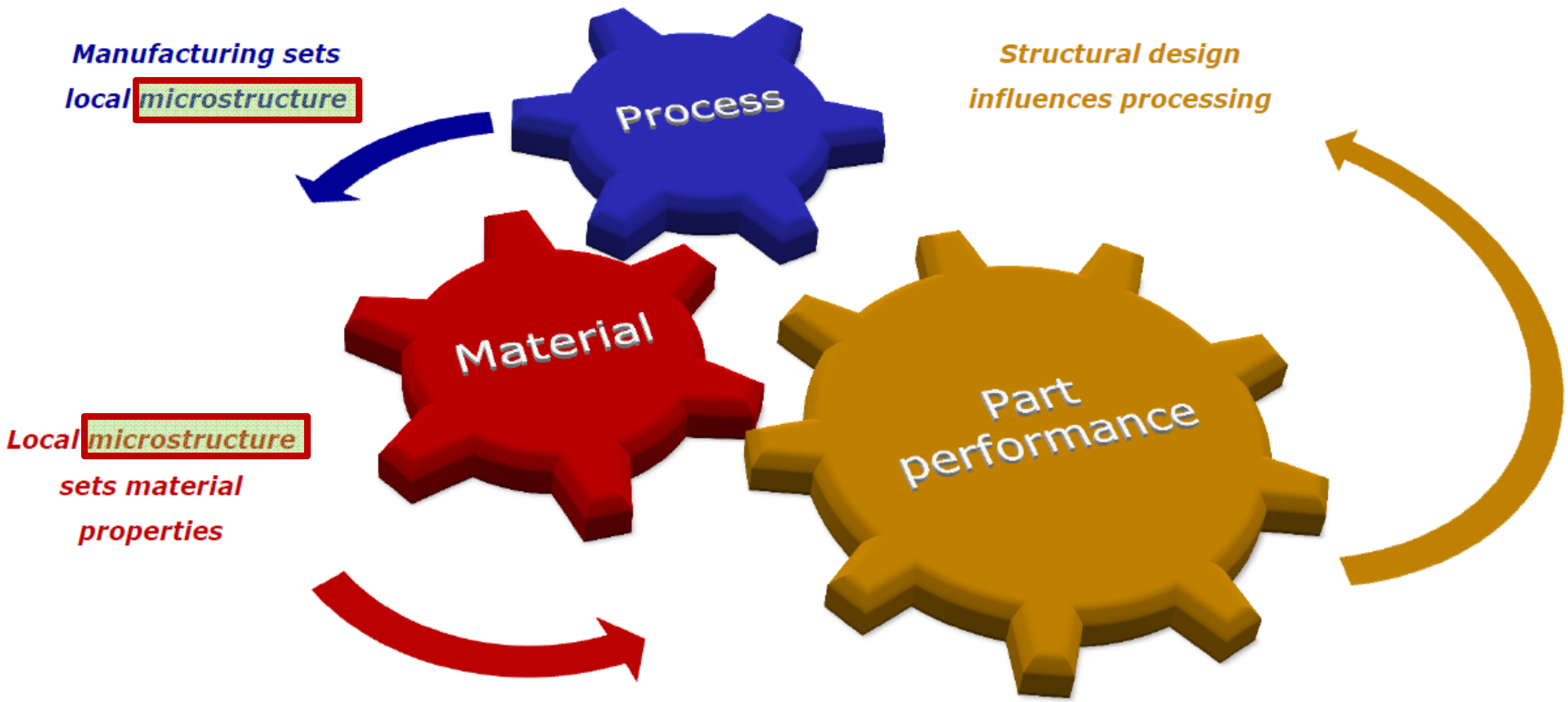


Capturing complex material properties



DIGIMAT-Approach

✓ Inter-dependencies in the Design of a Composite Part

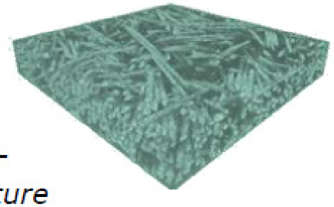


DIGIMAT calculates the material behavior and performance on a microstructural basis.

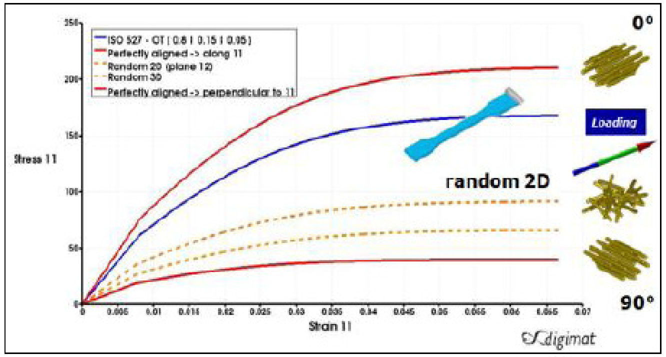
DIGIMAT-Approach

Short Fiber Reinforced Plastics

- ✓ **MICRO**
  - Material →

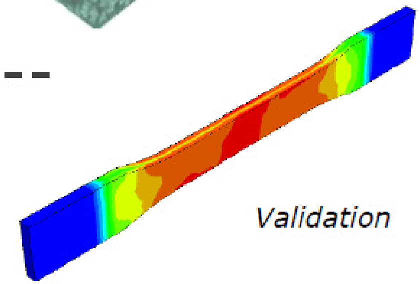


Micro-structure



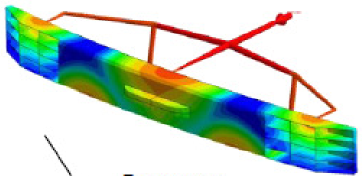
Material model

- ✓ **MACRO**
  - Dumbbell →

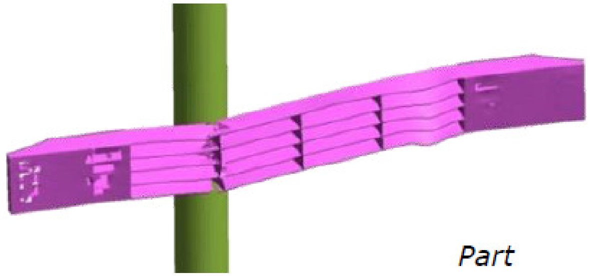


Validation

  - Part →



Process



Part performance

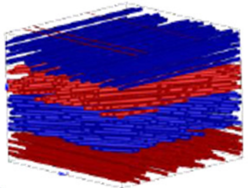
  - System

System level

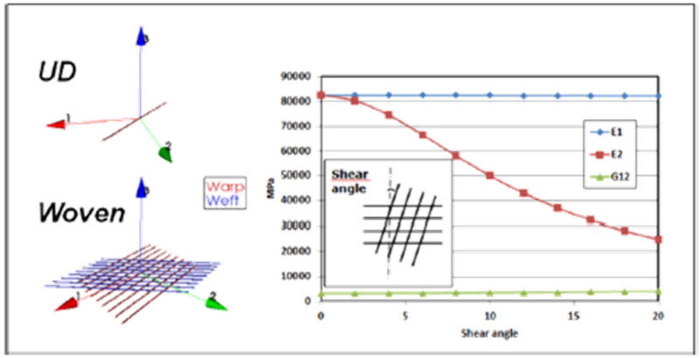
DIGIMAT-Approach

UD Composites

- ✓ **MICRO**
  - Material →

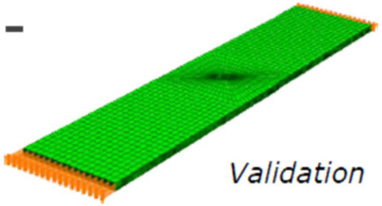


Micro-structure



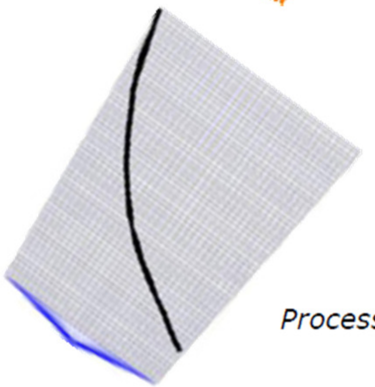
Material model

- ✓ **MACRO**
  - Dumbbell →

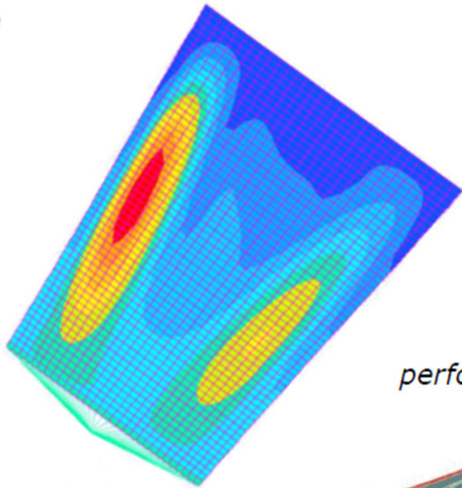


Validation

  - Part →

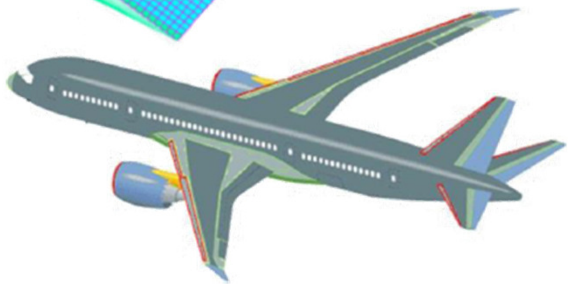


Process



Part performance

  - System

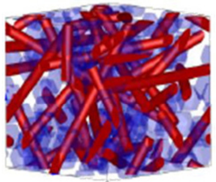


System level

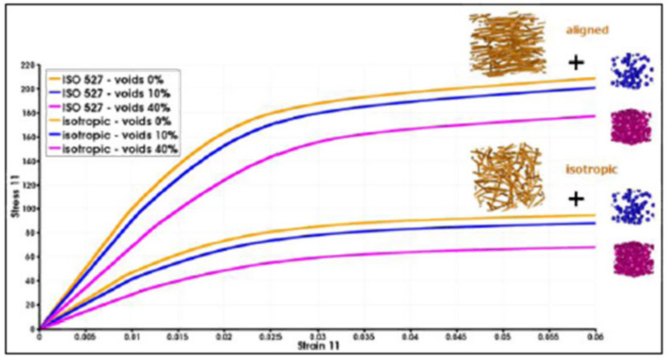
DIGIMAT-Approach

Mucell

- ✓ **MICRO**
  - Material →

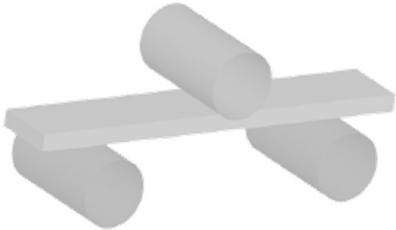


Micro-structure



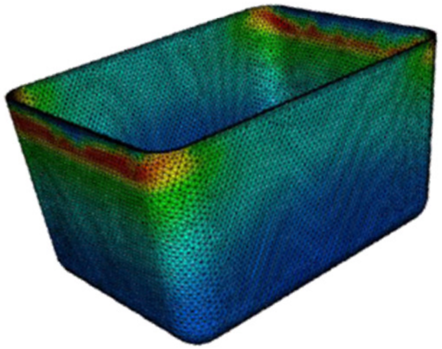
Material model

- ✓ **MACRO**
  - Dumbbell →

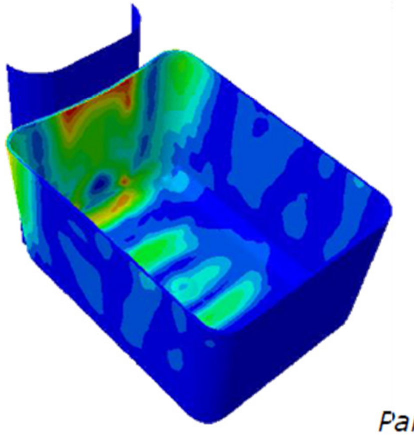


Validation

  - Part →



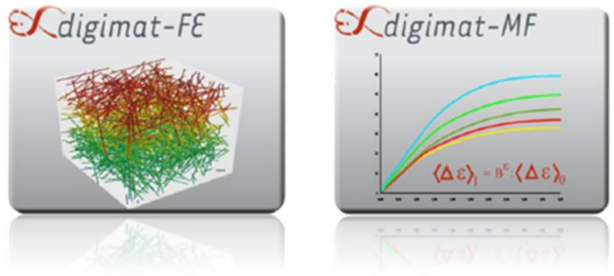
Process



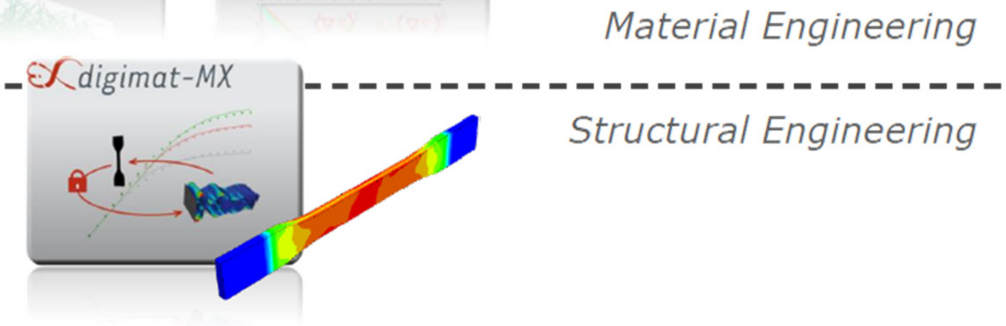
Part performance

Nonlinear Multiscale Modeling Platform

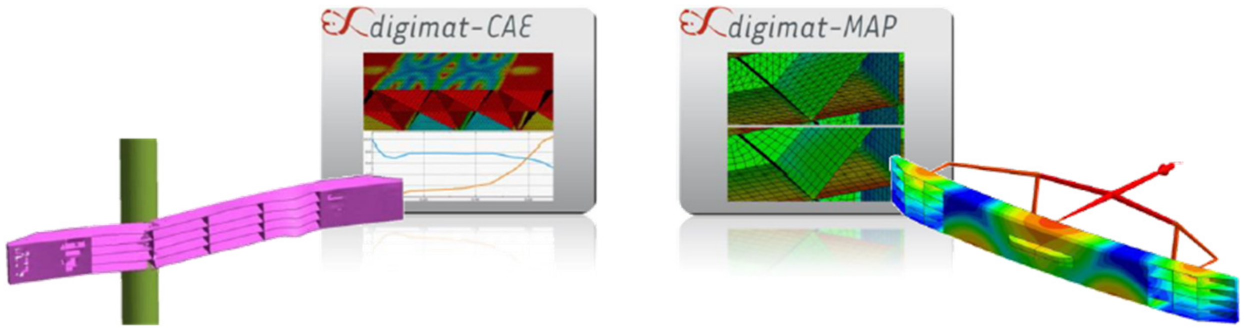
- ✓ **MICRO**
  - Virtual Material



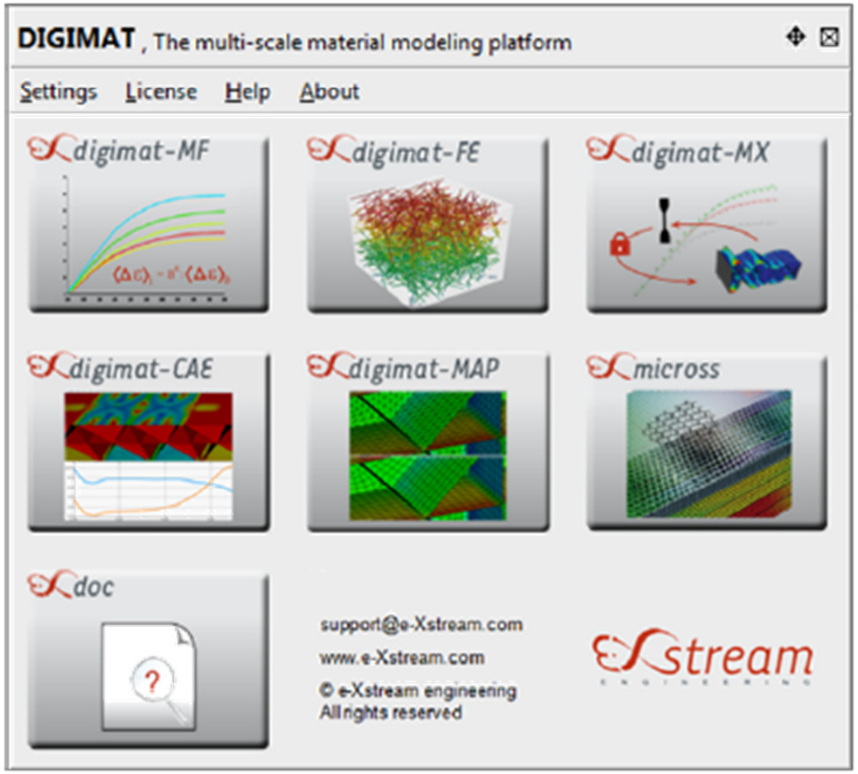
- ✓ **MACRO**
  - Reverse Engineering

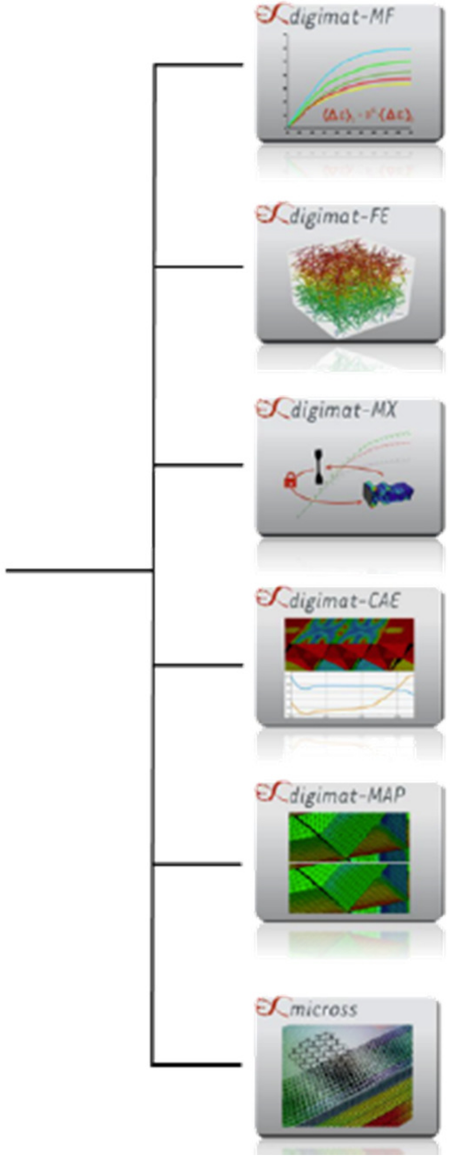


  - Interfaces
  - Mapping



DIGIMAT-Tools & Applications





Digimat- MF
to predict the nonlinear constitutive behavior of multi-phase material.

Digimat-FE
to perform Finite Element modeling of realistic Representative Volume Elements (RVE).

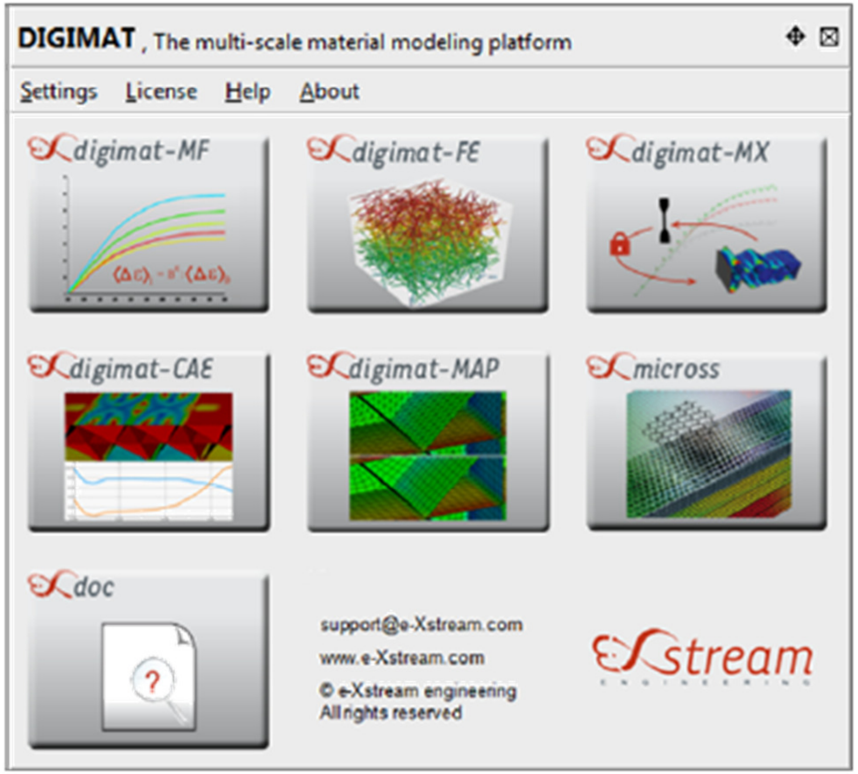
Digimat-MX
to reverse engineer, store, retrieve and securely exchange DIGIMAT material models.

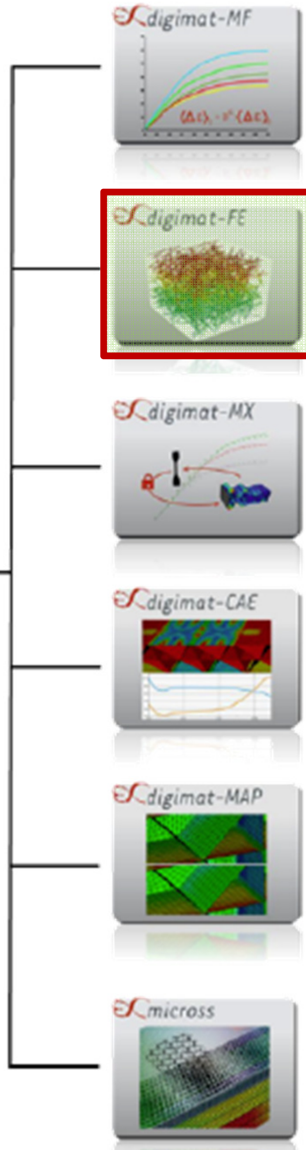
Digimat-CAE
to interface to all major processing and structural FEA software codes.

Digimat-MAP
to map data between dissimilar meshes.

Micross
to design honeycomb core composite sandwich panels based on FE analyses.

DIGIMAT-Tools & Applications





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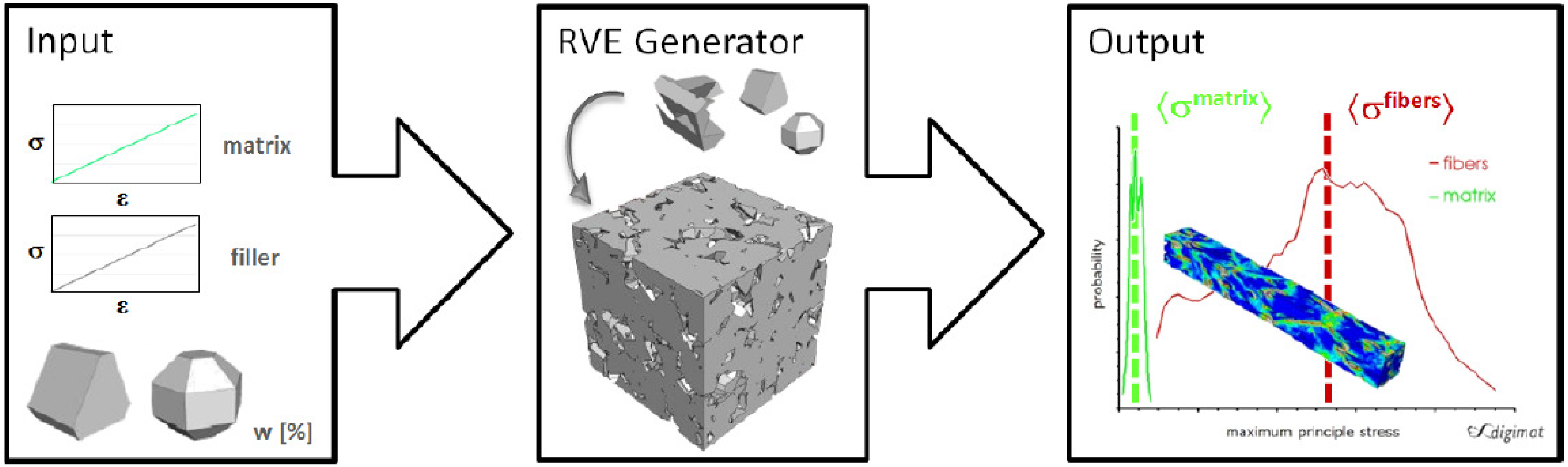
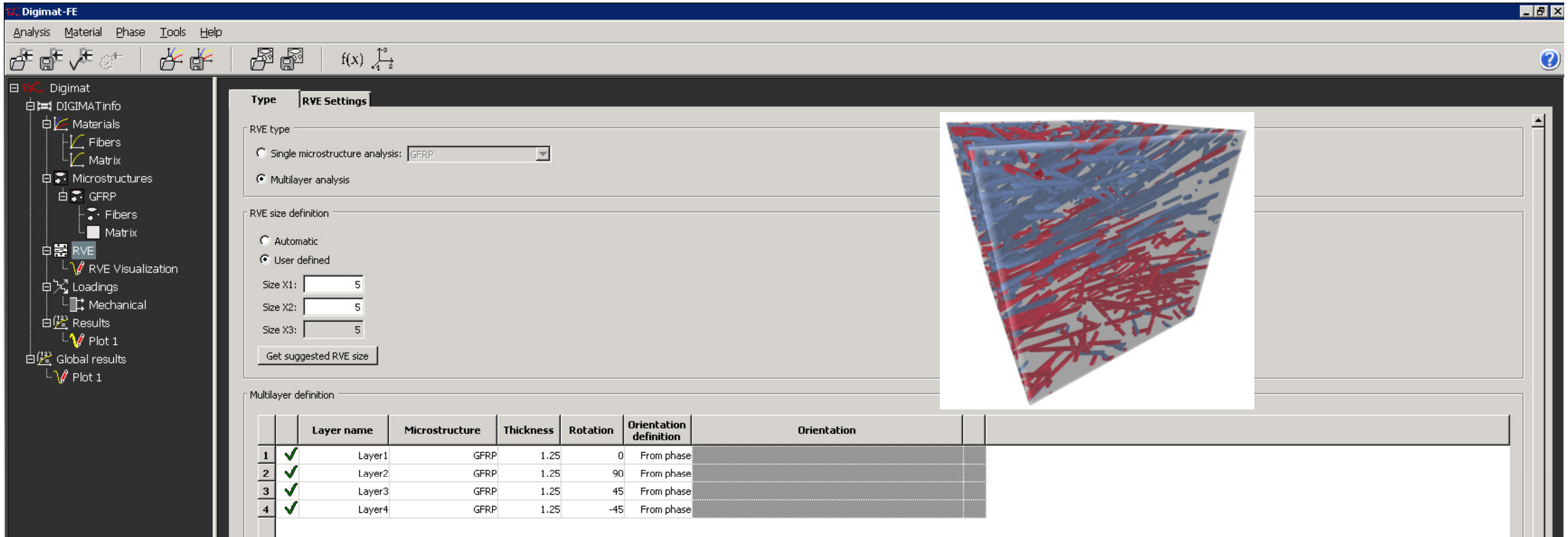
RVE generation and in depth analysis



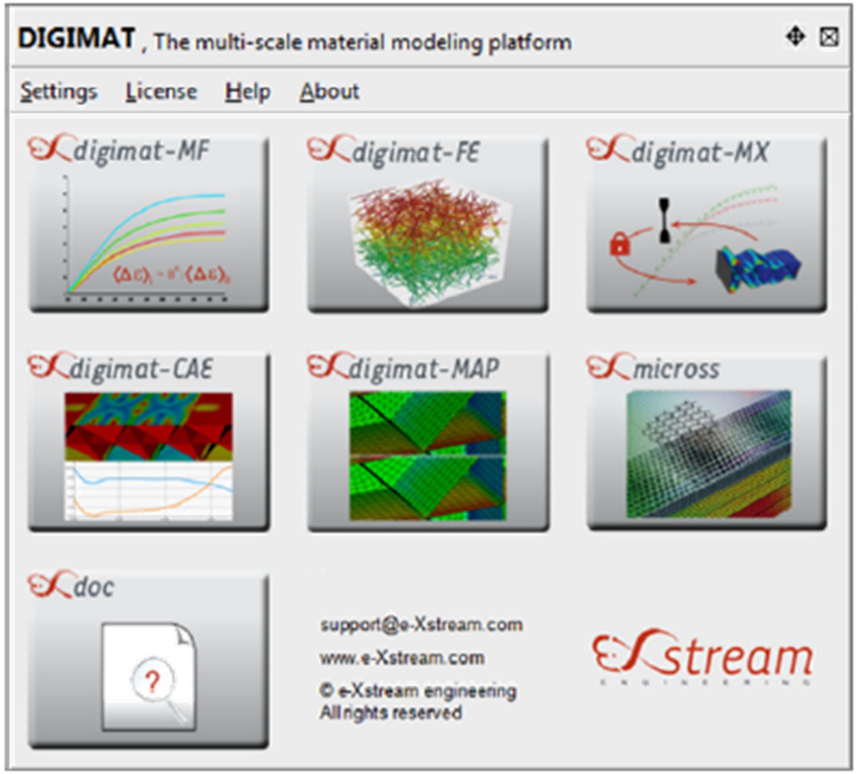
Input	RVE Generator	Output
Per-phase material properties + microstructure information + RVE settings	Random creation of complex RVEs according to set of parameters	Pre: RVE with complex and realistic microstructure Post: analysis of result file from external FEA solver

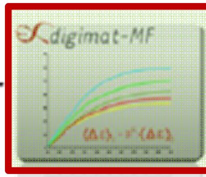
RVE generation and in depth analysis



- Output formats:
  - *.step
  - *.iges
  - *.breg
- Direkt link and meshing to:
  - ANSYS Workbench
  - Abaqus/CAE
- Different inclusion shapes & material models
- Different ways for microstructure definition (volume/mass content, multilayer, coating, orientation definition)
- Max. packing algorithm

DIGIMAT-Tools & Applications





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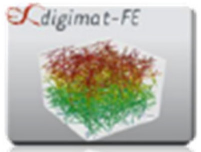
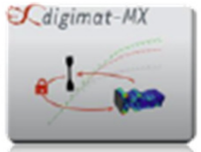
to predict the nonlinear constitutive behavior of multi-phase material.



Digimat-FE
to perform Finite Element modeling of realistic Representative Volume Elements (RVE).



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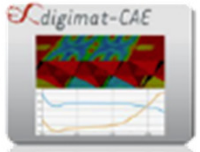

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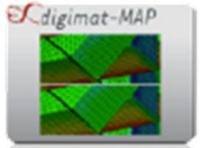

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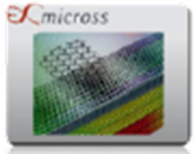
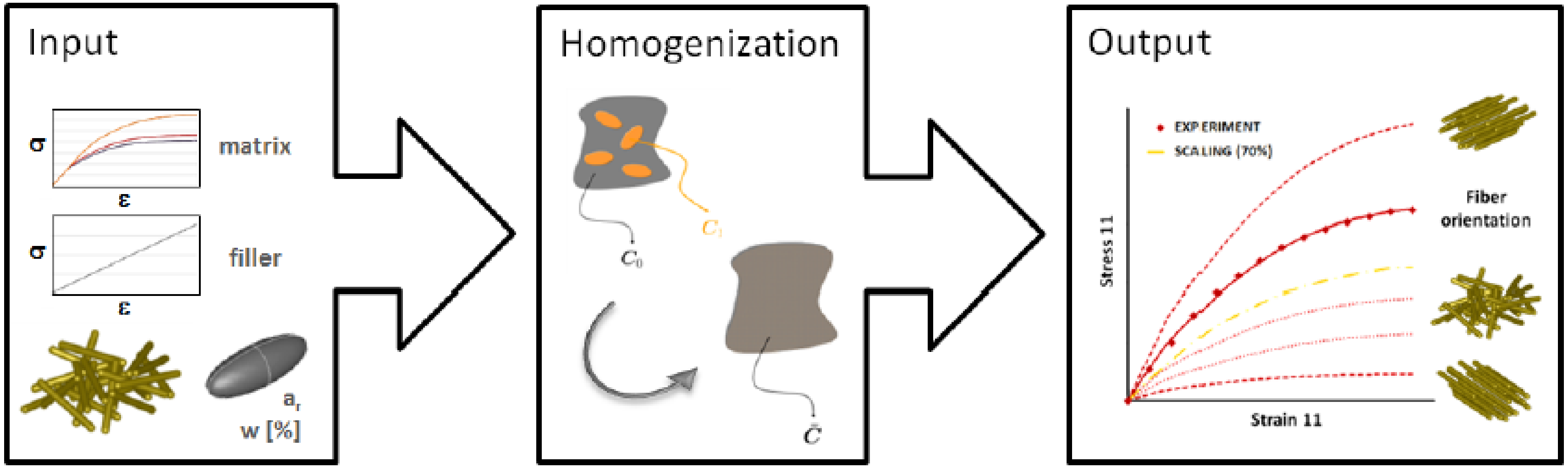


Micross
to design honeycomb core composite sandwich panels based on FE analyses.

✓ Material models dependent on the microstructure

- Mori-Tanaka homogenization
- Influence of fillers: amount, shape, orientation, ...



Per-phase material properties + microstructure information

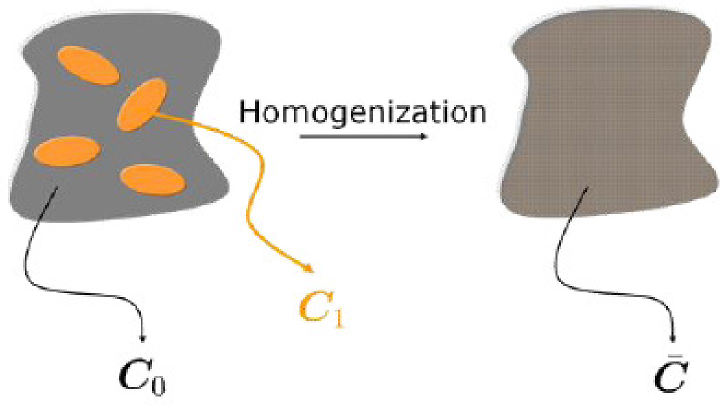
State-of-the-art homogenization methods

DIGIMAT material model sensitive to composite microstructure

Multi-Phase Materials

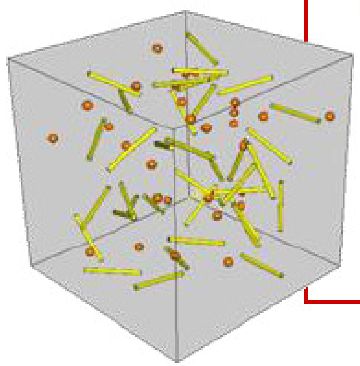
✓ Phases

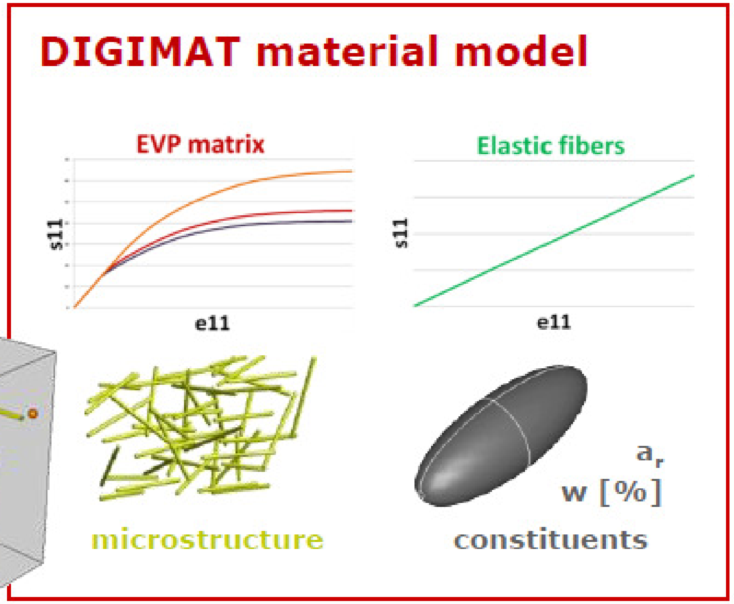
- Material 1 [matrix]
- Material 2 [fibers]



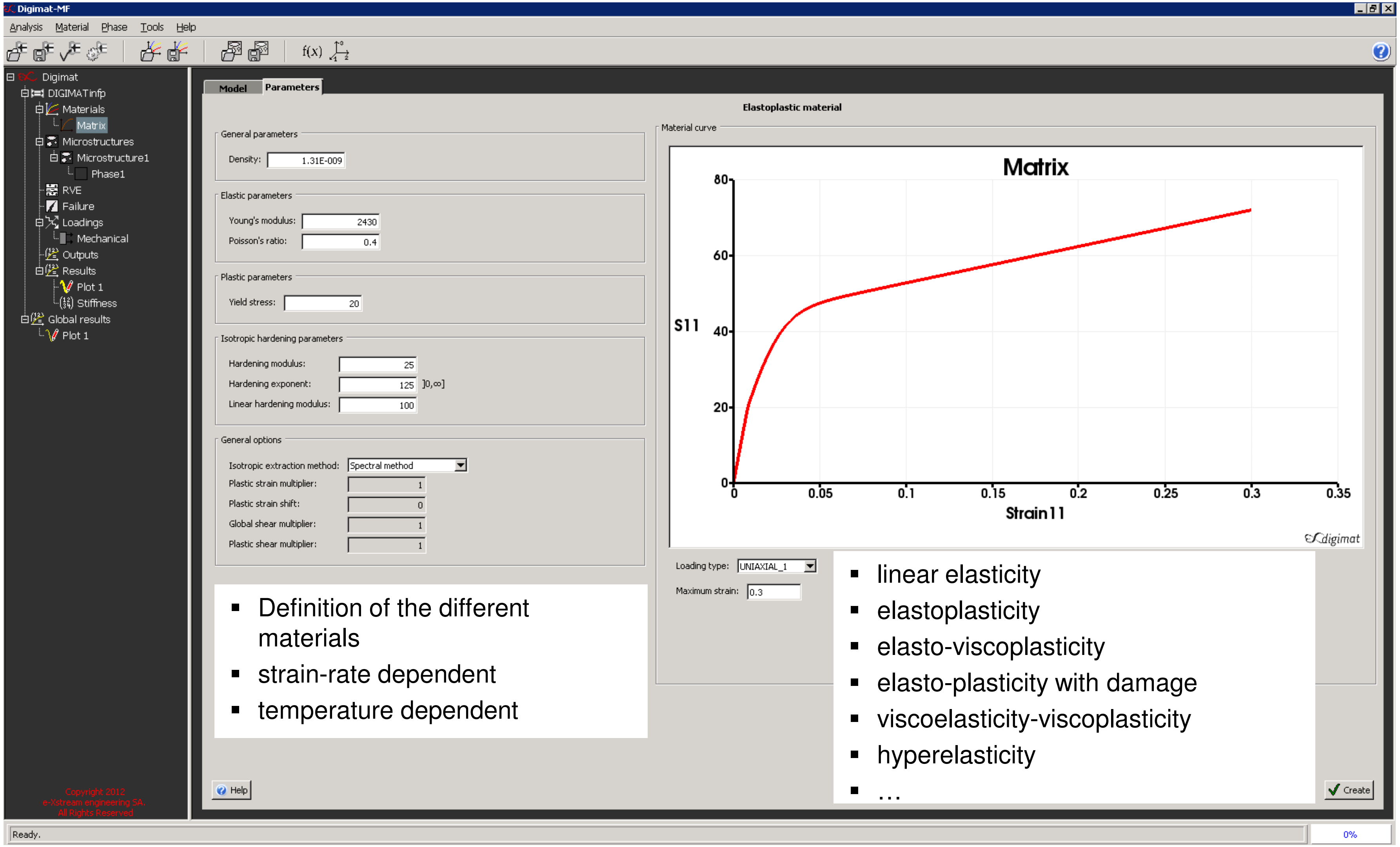
✓ Microstructure

- Matrix
- Inclusions
  - Shape
  - Orientation





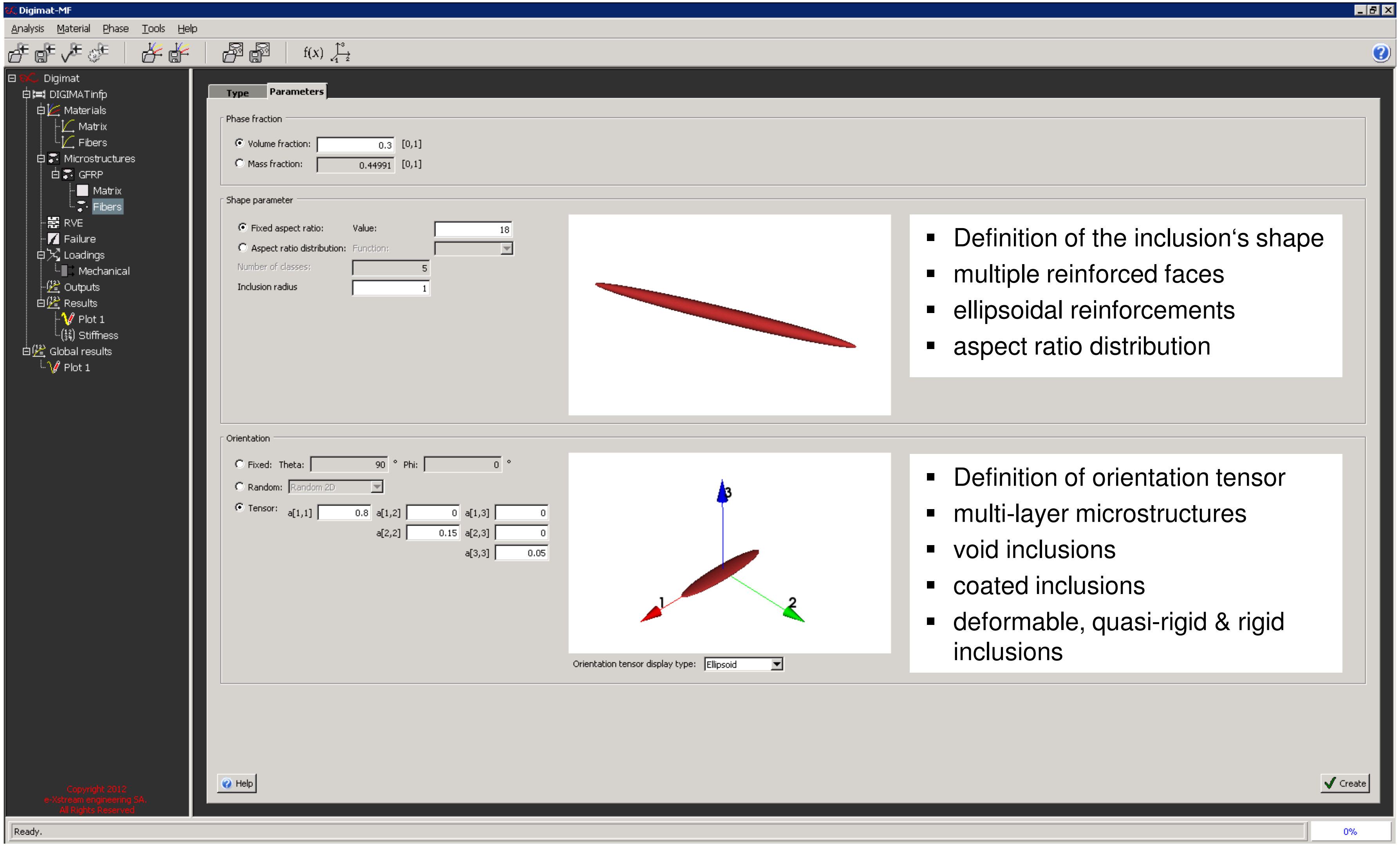
Material definition in MF



- Definition of the different materials
- strain-rate dependent
- temperature dependent

- linear elasticity
- elastoplasticity
- elasto-viscoplasticity
- elasto-plasticity with damage
- viscoelasticity-viscoplasticity
- hyperelasticity
- …

Material definition in MF – matrix & inclusion definition

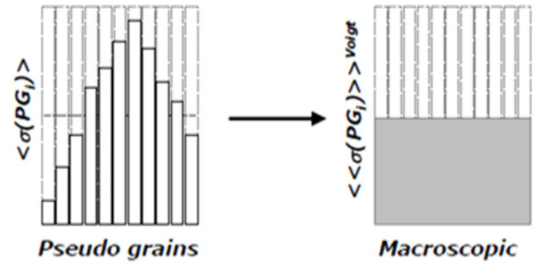


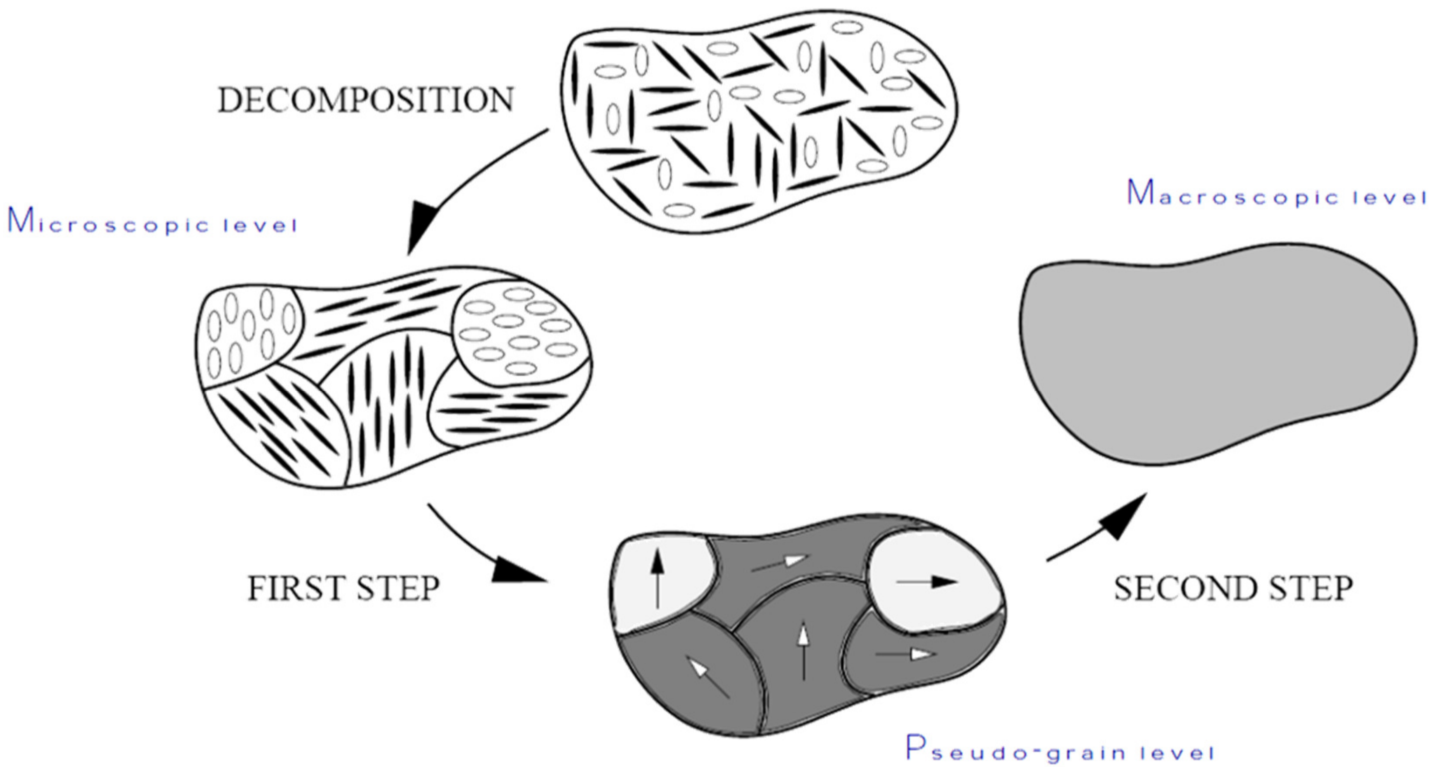
- Definition of the inclusion's shape
- multiple reinforced faces
- ellipsoidal reinforcements
- aspect ratio distribution

- Definition of orientation tensor
- multi-layer microstructures
- void inclusions
- coated inclusions
- deformable, quasi-rigid & rigid inclusions

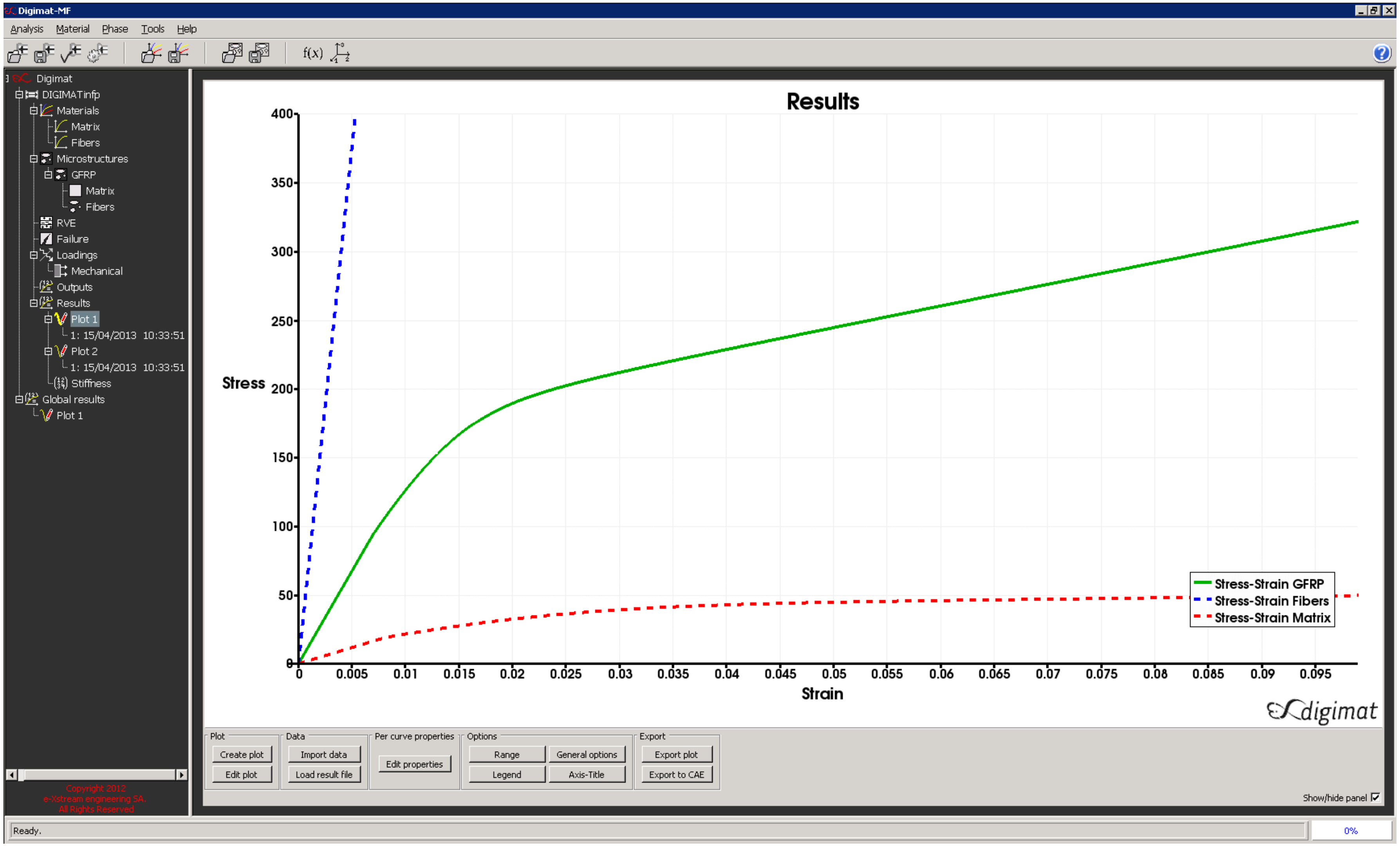
Material definition in MF – homogenization

- **Multi-Phase Materials**
  - ✓ Stepwise homogenization

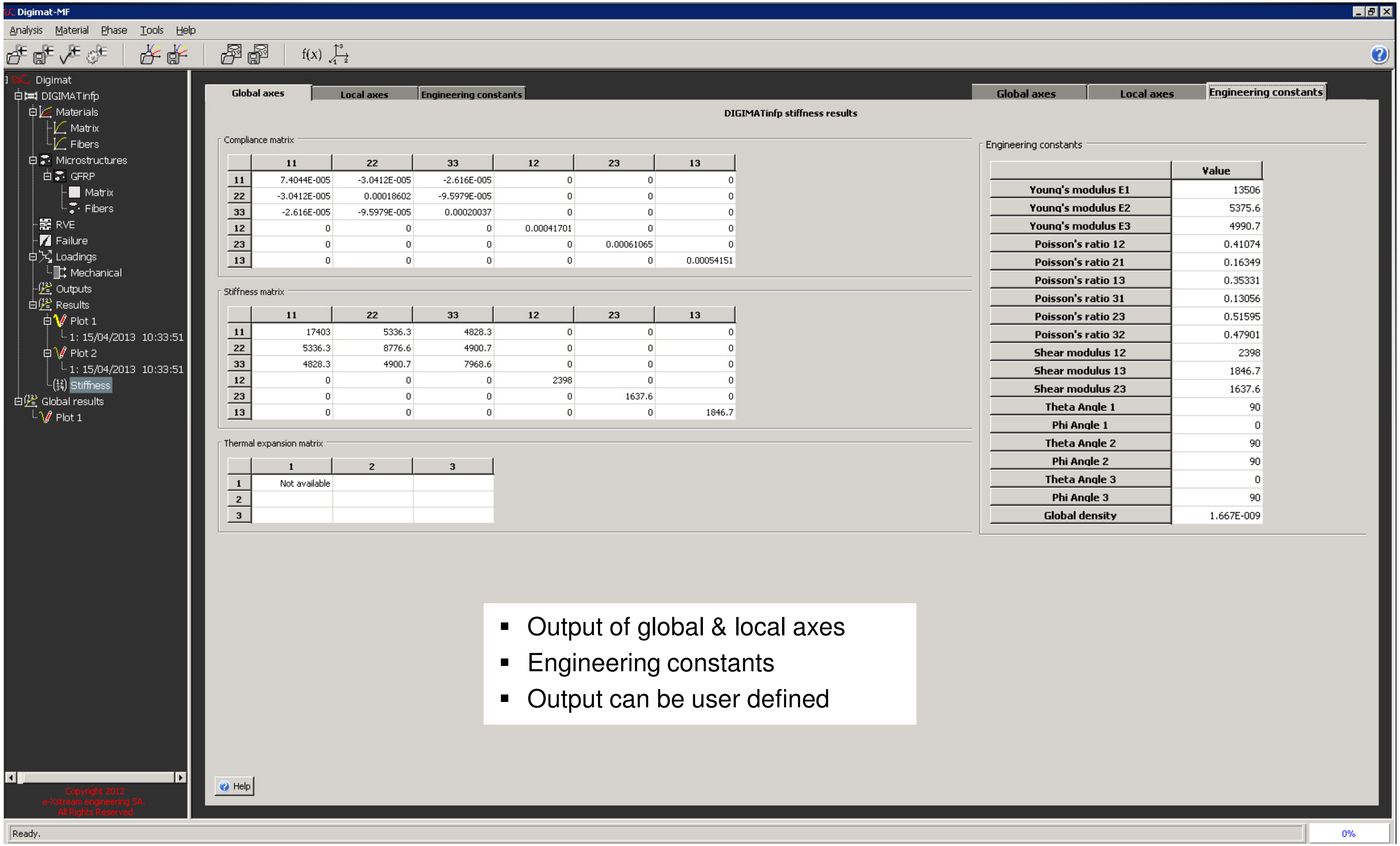




Material definition in MF – resulting parameter



Material definition in MF – resulting parameter



DIGIMATinfp stiffness results

Compliance matrix

	11	22	33	12	23	13
11	7.4044E-005	-3.0412E-005	-2.616E-005	0	0	0
22	-3.0412E-005	0.00018602	-9.5979E-005	0	0	0
33	-2.616E-005	-9.5979E-005	0.00020037	0	0	0
12	0	0	0	0.00041701	0	0
23	0	0	0	0	0.00061065	0
13	0	0	0	0	0	0.00054151

Stiffness matrix

	11	22	33	12	23	13
11	17403	5336.3	4828.3	0	0	0
22	5336.3	8776.6	4900.7	0	0	0
33	4828.3	4900.7	7968.6	0	0	0
12	0	0	0	2398	0	0
23	0	0	0	0	1637.6	0
13	0	0	0	0	0	1846.7

Thermal expansion matrix

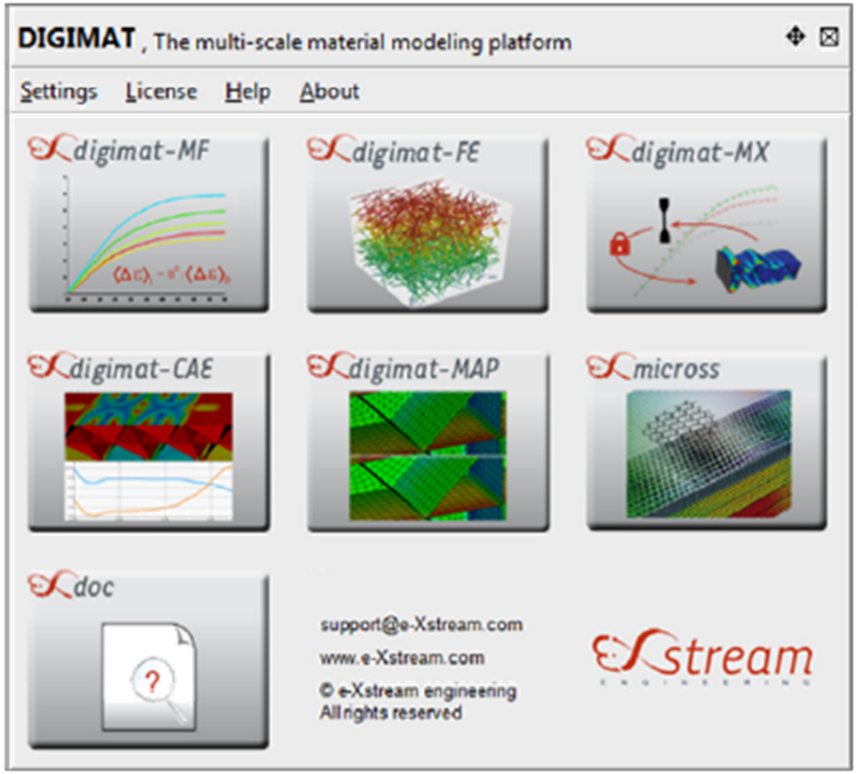
	1	2	3
1	Not available		
2			
3			

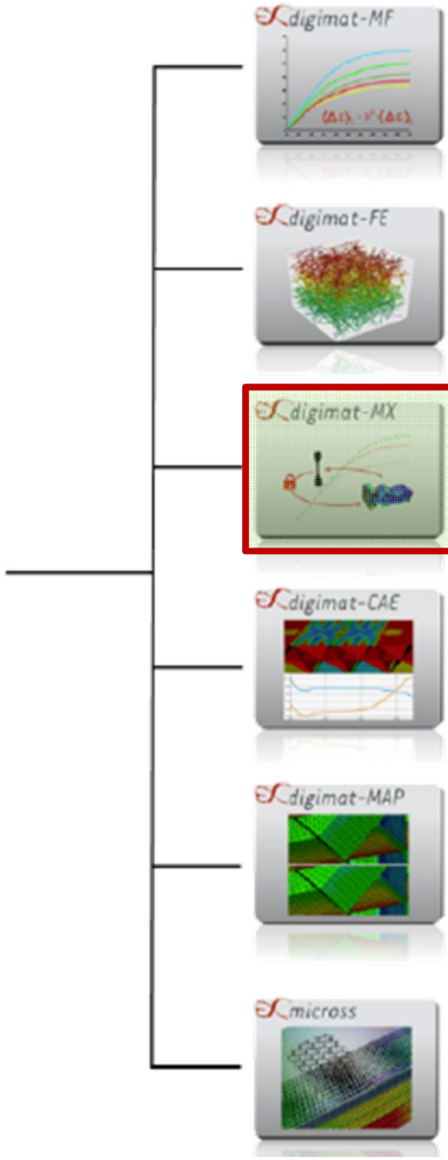
Engineering constants

	Value
Young's modulus E1	13506
Young's modulus E2	5375.6
Young's modulus E3	4990.7
Poisson's ratio 12	0.41074
Poisson's ratio 21	0.16349
Poisson's ratio 13	0.35331
Poisson's ratio 31	0.13056
Poisson's ratio 23	0.51595
Poisson's ratio 32	0.47901
Shear modulus 12	2398
Shear modulus 13	1846.7
Shear modulus 23	1637.6
Theta Angle 1	90
Phi Angle 1	0
Theta Angle 2	90
Phi Angle 2	90
Theta Angle 3	0
Phi Angle 3	90
Global density	1.667E-009

- Output of global & local axes
- Engineering constants
- Output can be user defined

digimat





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to predict the nonlinear constitutive behavior of multi-phase material.

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to perform Finite Element modeling of realistic Representative Volume Elements (RVE).

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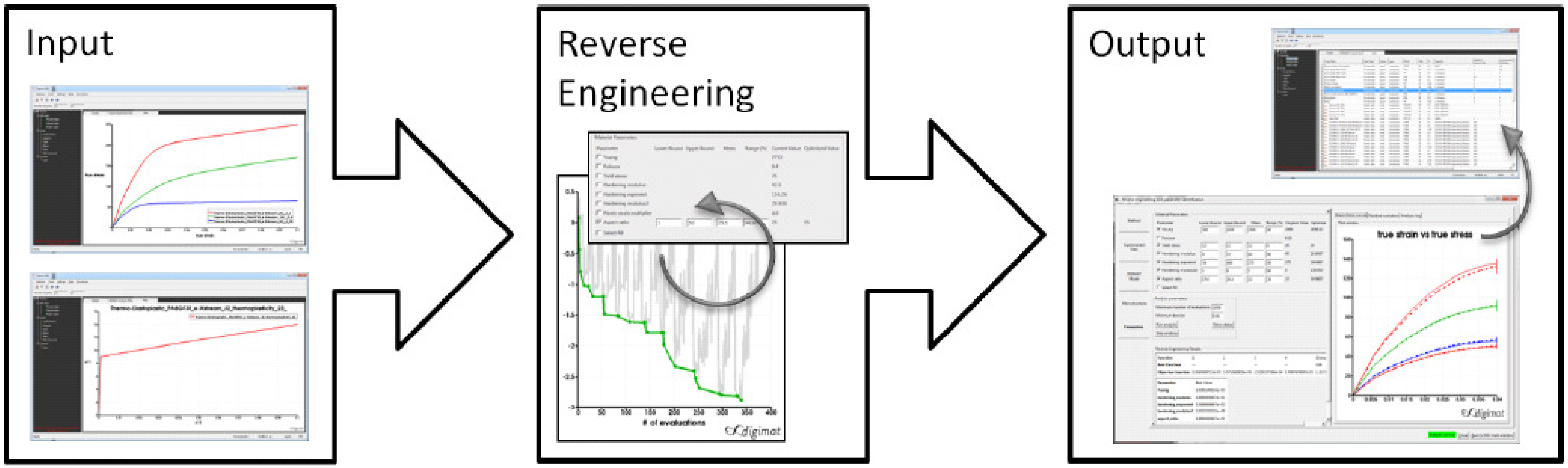
to reverse engineer, store, retrieve and securely exchange DIGIMAT material models.

Digimat-CAE
to interface to all major processing and structural FEA software codes.

Digimat-MAP
to map data between dissimilar meshes.

Micross
to design honeycomb core composite sandwich panels based on FE analyses.

Parameter fitting in MX – overview



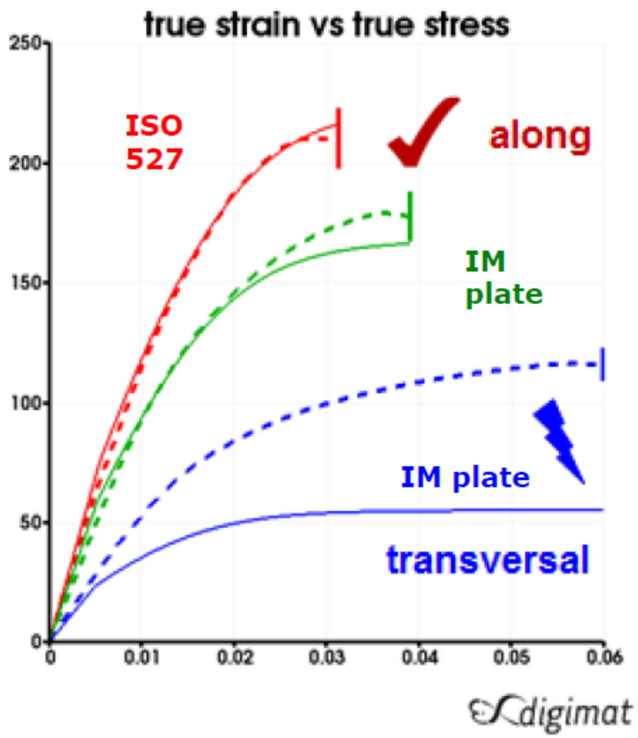
Experimental data, DIGIMAT material models stored in database

Calibration of DIGIMAT models based on experimental data

Calibrated DIGIMAT Material Model, stored in database and ready to be shared and used

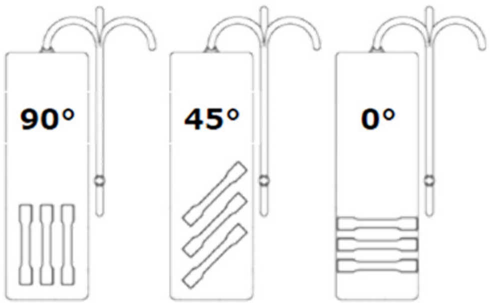
Parameter fitting in MX – semi-quantitative approach

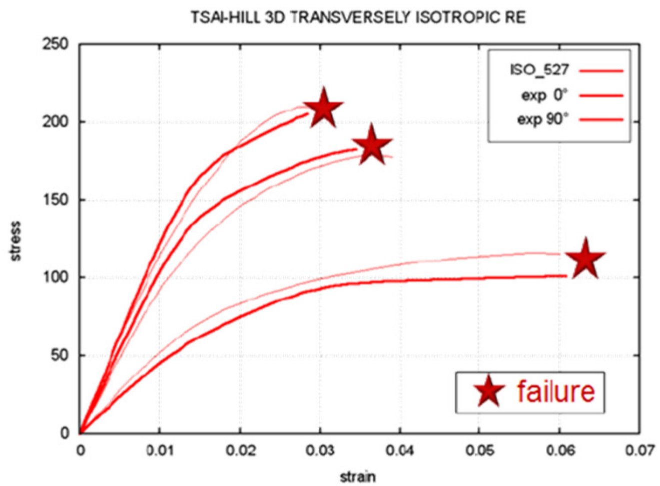
- „ISO 527"
  - ✓ Short Fiber Reinforced Plastics
    - **Semi-quantitative**
      - Based on CAMPUS (or similar)
      - **Non-expert**
      - **Quick & easy**
      - **Early design**
      - Only stiffness
      - Highly aligned states are better described than transversal



Parameter fitting in MX – qualitative approach

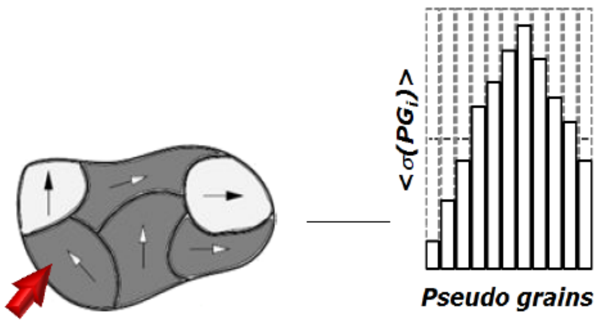
- „Injection Molded Plate"
  - ✓ Short Fiber Reinforced Plastics
    - **Qualitative**
      - Based on anisotropic measurements
      - **Expert**
      - **Detailed**
      - **Validation**
      - Stiffness & failure
      - Global fit of material behavior

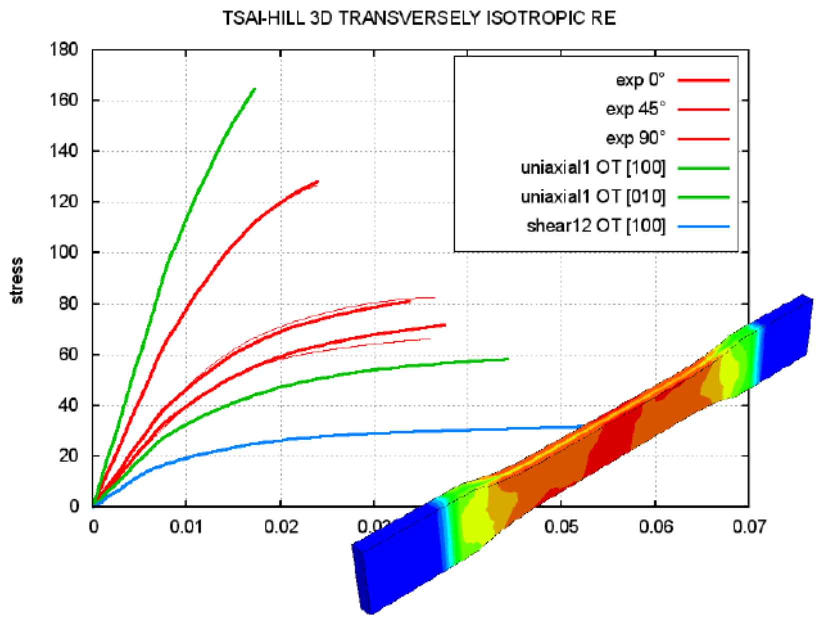




Parameter fitting in MX – qualitative approach

- „Injection Molded Plate“
  - ✓ Short Fiber Reinforced Plastics
    - Based on pseudo grains (FPGF)
    - Described on composite level
      - Tsai-Hill 3D
      - Transversely isotropic
      - Strain based

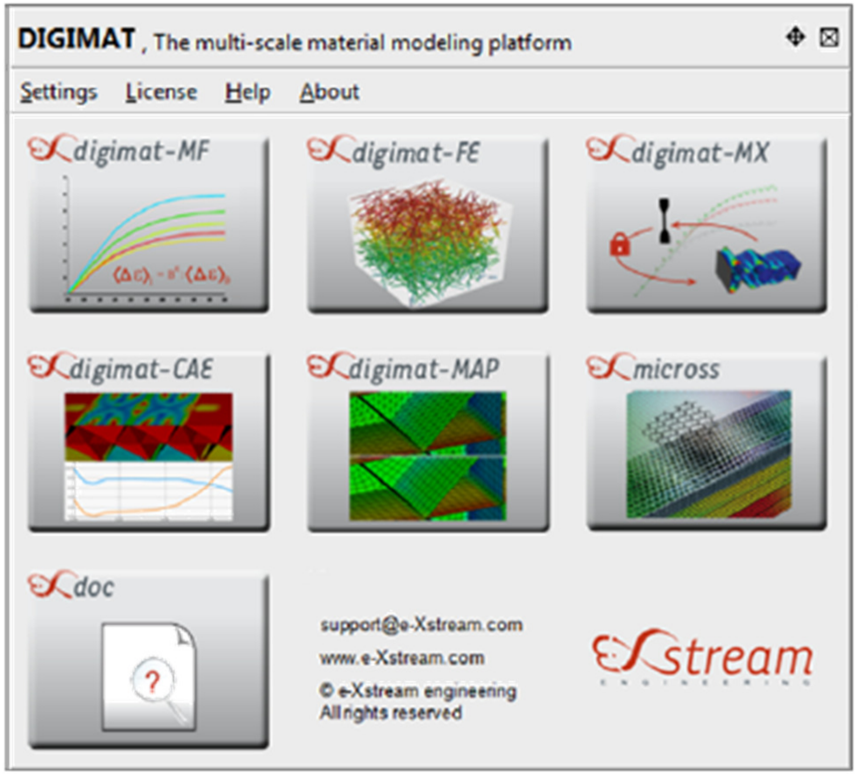


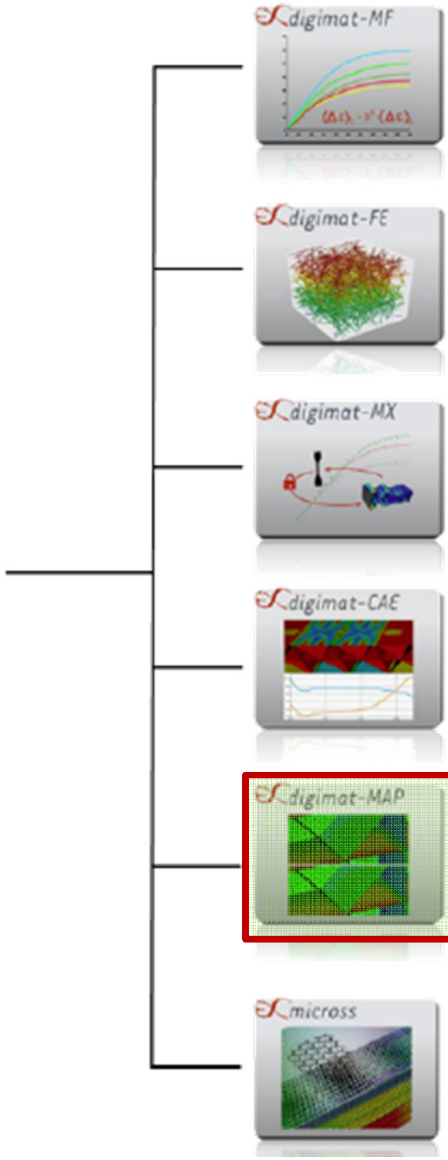


Parametrize & eXchange DIGIMAT material models

✓ **Public data**

- Ready-to-use DIGIMAT models
- Experimental data for parametrization of DIGIMAT models





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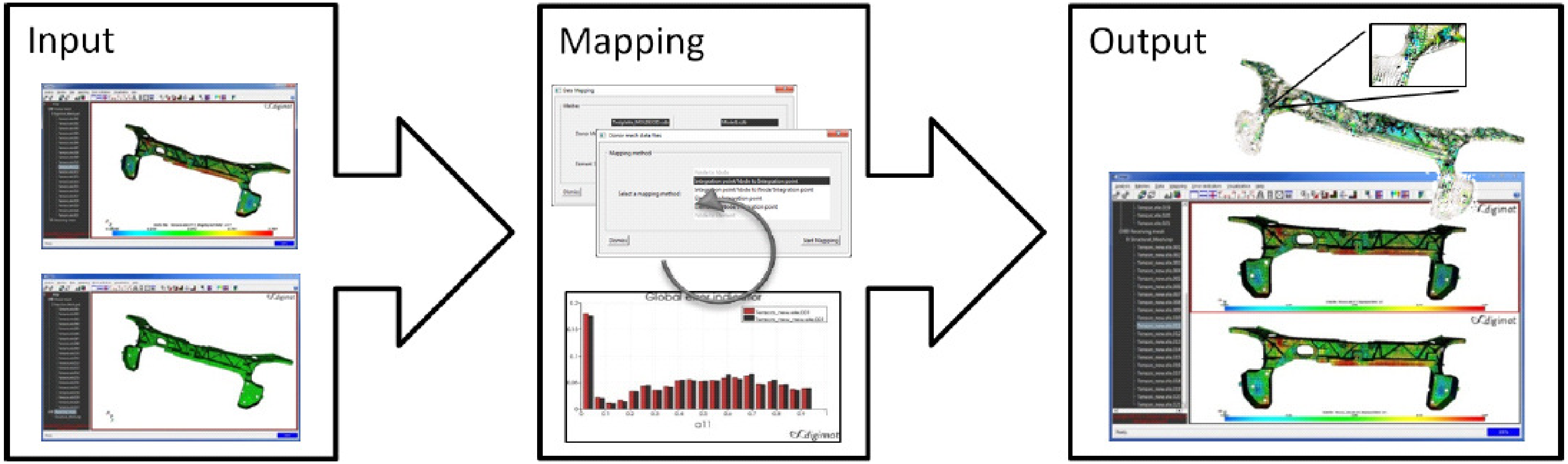
Mapping from process simulation onto crash mesh



Mesh & properties from processing simulation + Mesh for structural FEA

Robust mapping methods

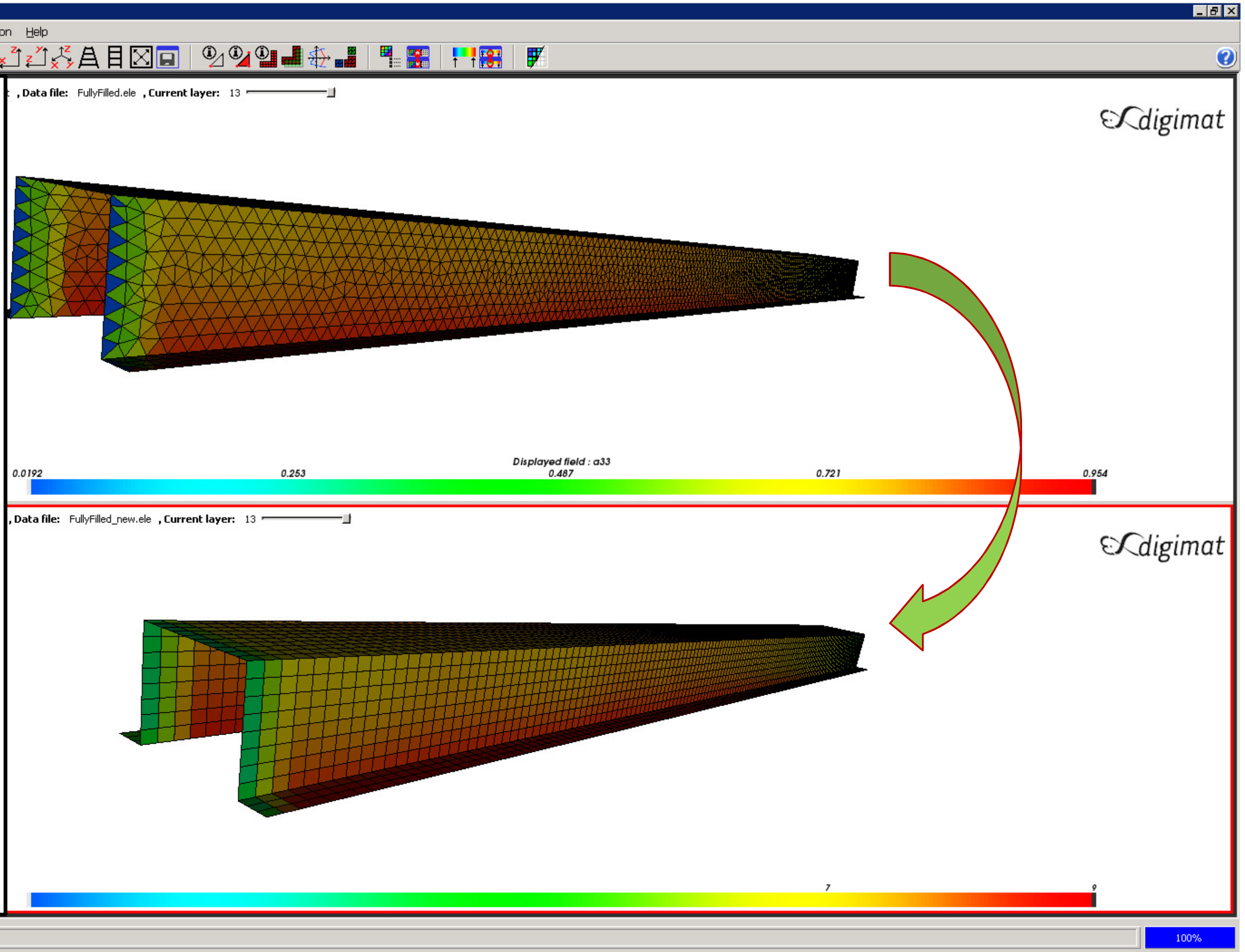
Mapped properties on structural FEA mesh + strong visualization of results

Mapping from process simulation onto crash mesh

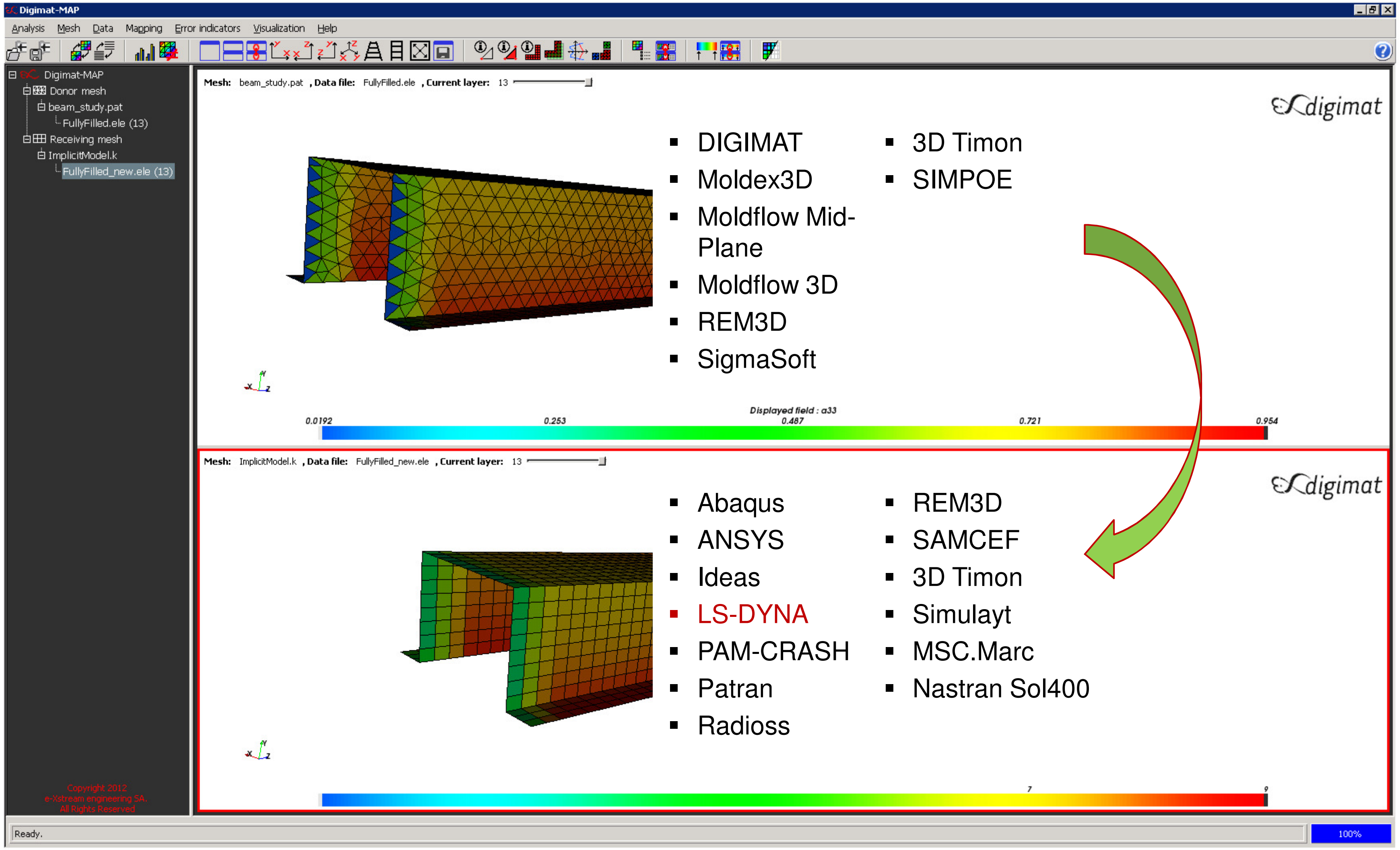
- From mid-plane to multi-layered shell
- Between continuum 3D elements
- Across the shell thickness

- Fiber orientation tensors
- Residual stresses
- Temperature fileds
- Weld lines

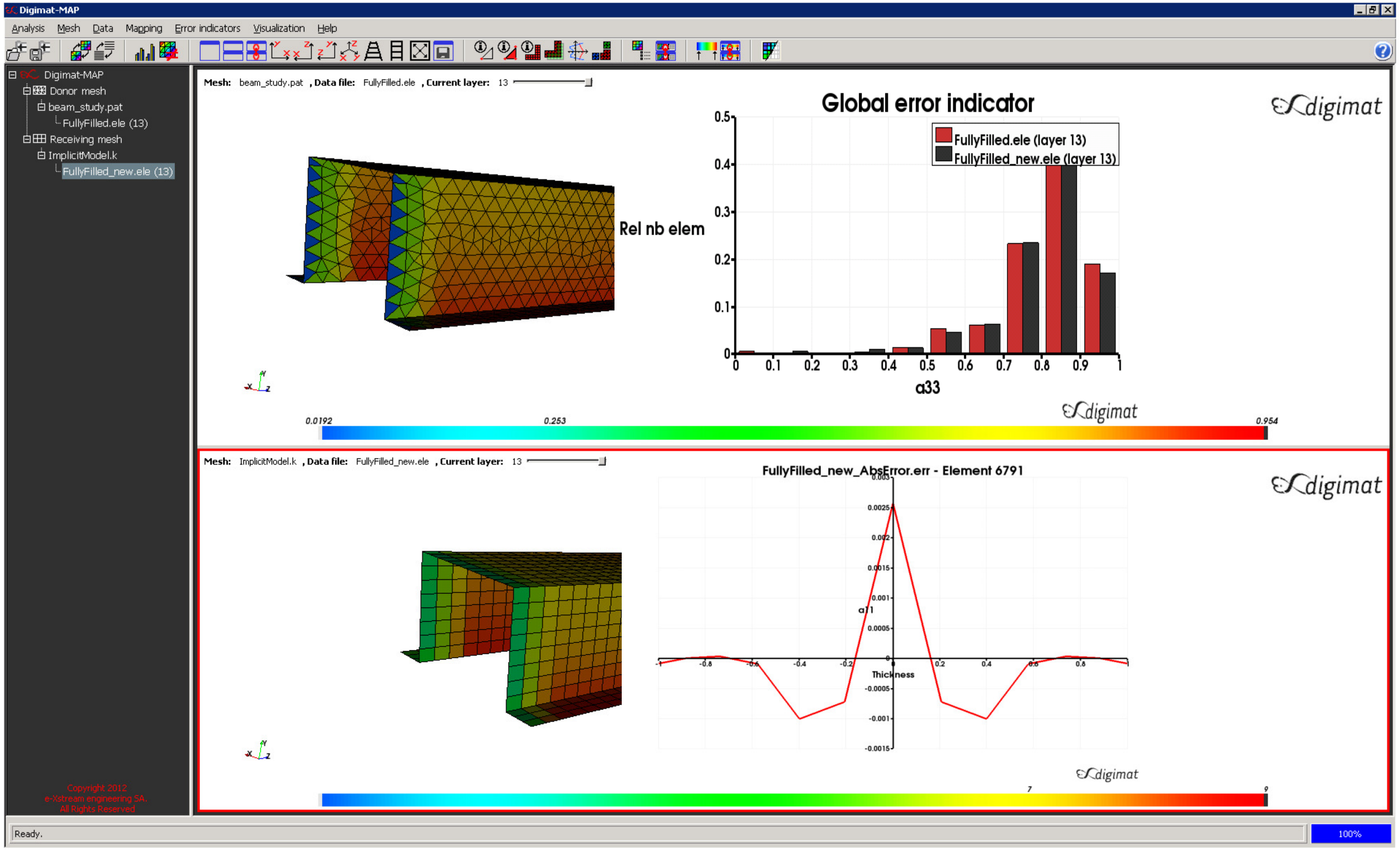
- Donor:
  - Tetra or TRIA
  - Hexa & Wedge
- Receiver
  - Tetra or TRIA
  - Hexa or QUAD
  - Wedge



Mapping from process simulation onto crash mesh

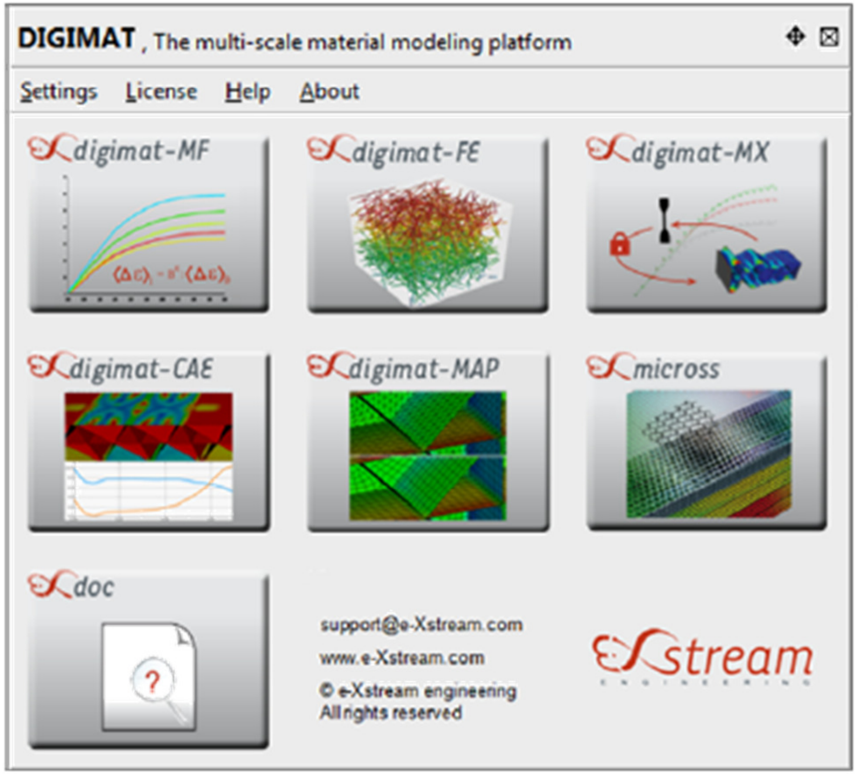


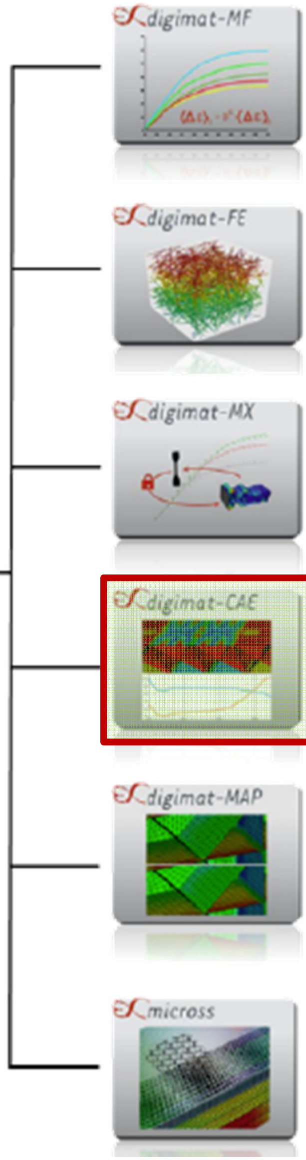
Mapping from process simulation onto crash mesh



DIGIMAT-Tools & Applications

digimat-CAE





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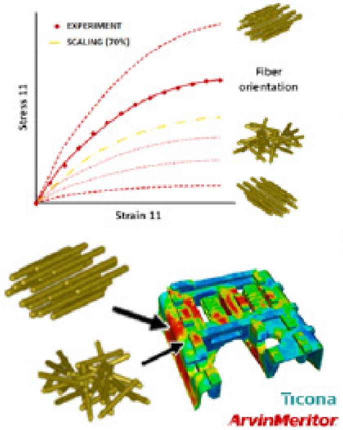
Coupling Micro- & Macromechanics

Input



DIGIMAT material model + local microstructure (from processing simulation)

Interfaces

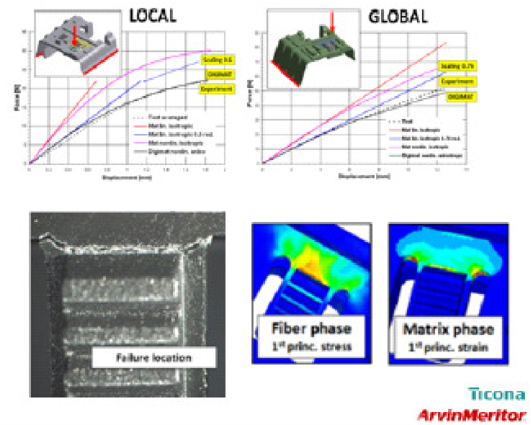
Injection Molding

FEA

Draping

Weakly or strongly coupled analyses with implicit or explicit FEA solvers

Result



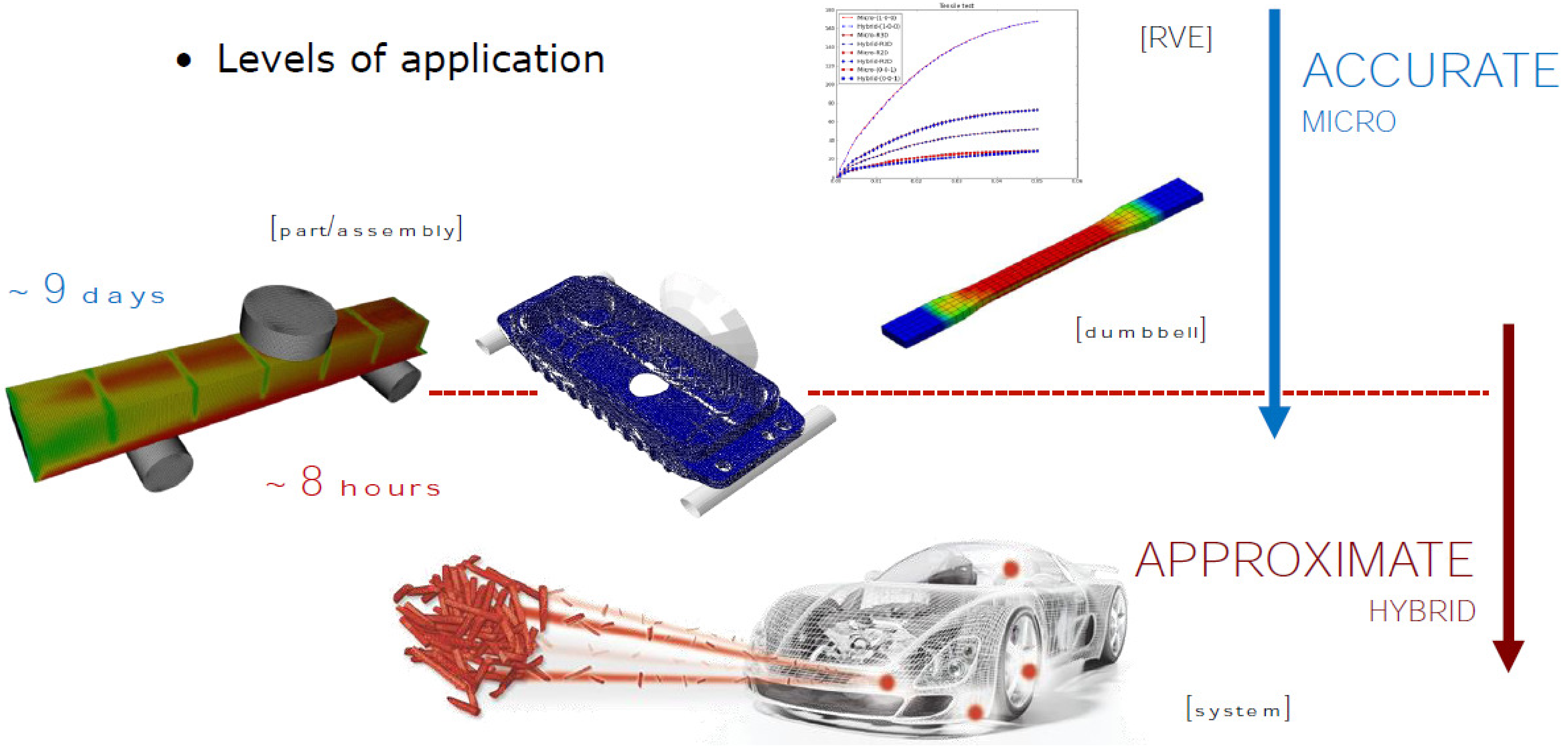
Predictive, high quality results for composite structures

Micro - vs. Macro - Approach

✓ Hybrid approach: Trade-Off between accuracy and computation time

✓ CPU time can become critical

- Levels of application

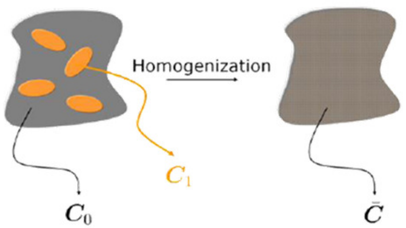


Micro - Approach

The full homogenization approach operates at each integration point & time of analysis

✓ Micro-/Macro Transition:

- Use of homogenization method to predict the macro constitutive behavior of the RVE.



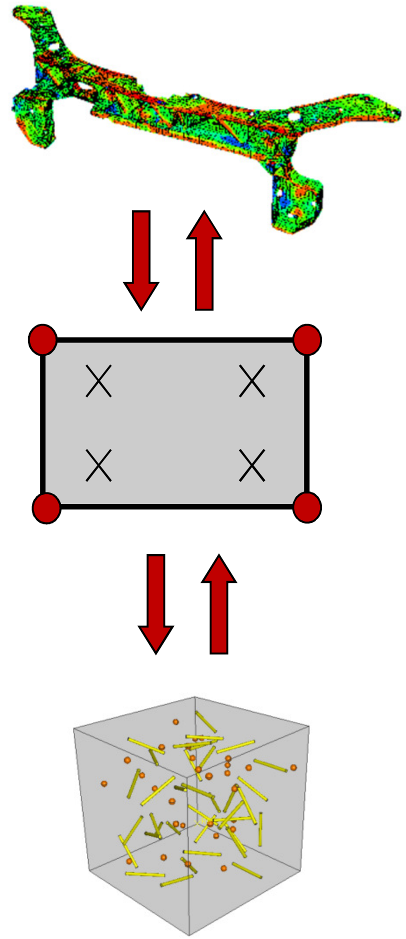
✓ Macro FEA:

- Perform classical continuum mechanics computations at macro scale with macro constitutive response.

FE-model level:

Element level:

Material level:



Hybrid - Approach

Reduction of information exchange to the macroscopic level.

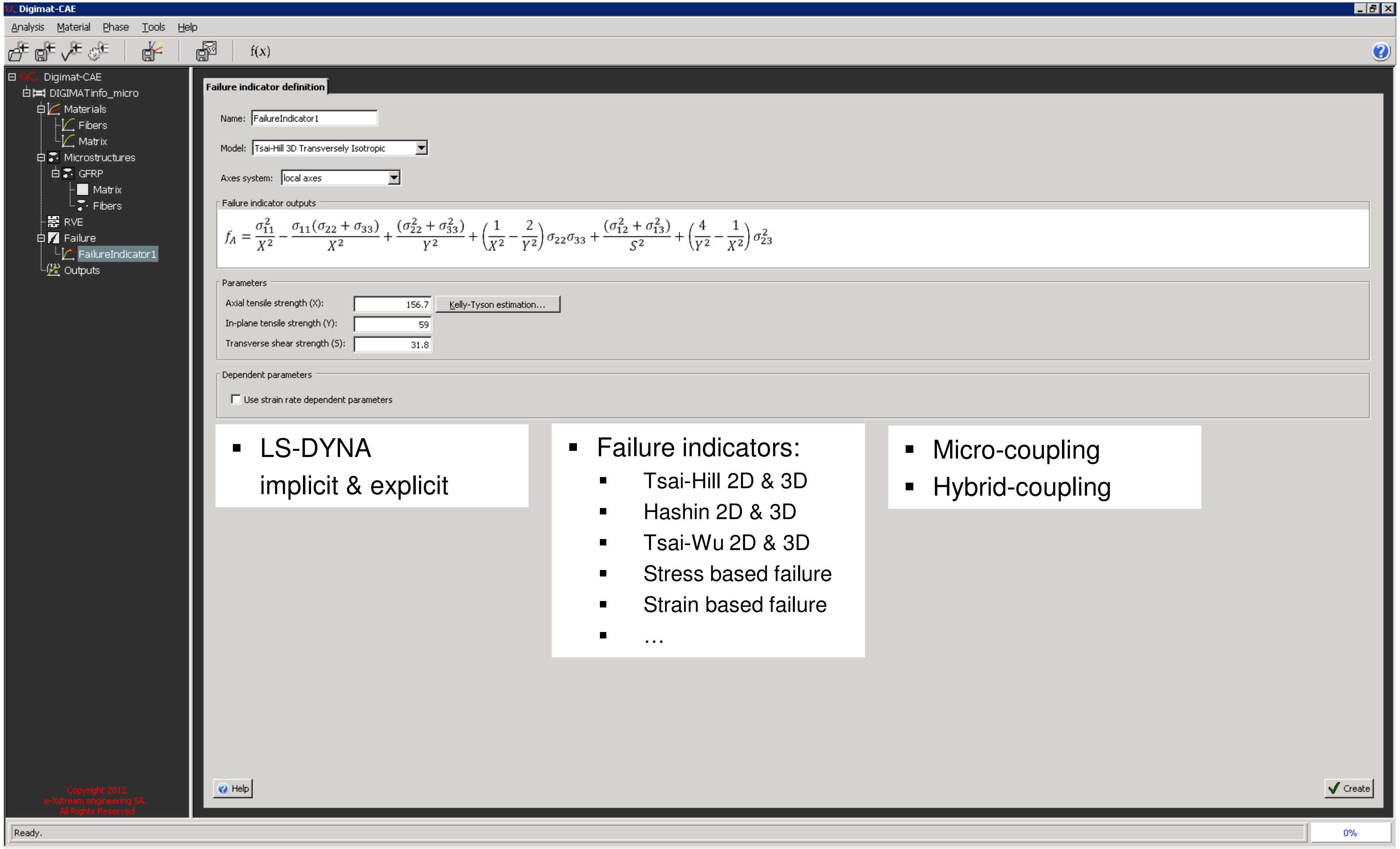
✓ Macroscopical properties are pre-computed

- DIGIMAT-CAE interface used to communicate with the structural code at each iteration of the overall computation
- Per-phase micro results are skipped
- Only available for two-phase composites so far
- Reverse engineering to deliver a good approximation to the exact micro solution

✓ Hybrid solution provides a great speed-up

- ~ 20 x for explicit analysis with elasto (visco-) plastic materials
- Further speed-up expected for release 4.4.1 (April 2013)
- No convergence trouble due to the skipped homogenization
- Failure is based on state-of-the-art **F**irst **P**seudo **G**rain **F**ailure (FPGF) model for randomly distributed short fibers

Including failure mechanisms



- LS-DYNA
  implicit & explicit

- Failure indicators:
  - Tsai-Hill 2D & 3D
  - Hashin 2D & 3D
  - Tsai-Wu 2D & 3D
  - Stress based failure
  - Strain based failure
  - …

- Micro-coupling
- Hybrid-coupling

Linking DIGIMAT to LS-DYNA – DIGIMAT output files

✓ DIGIMAT-output:

- *.log – File

Process documentation

(material data, micro-/hybrid approach, failure information…)

- *.dyn – File

LS-DYNA User material

```
*MAT_USER_DEFINED_MATERIAL_MODELS
$       MID        RO        MT       LMC       NHV    IORTHO     IBULK        IG
          1 1.67E-009        41         2        77         0         1         2
$     IVECT     IFAIL
          1         1
$     P1(K)     P2(G)
 4.46E+004 3.07E+004
```

- *.mat – File

Material information for calculation

```
ANALYSIS
name = DIGIMATinfo
type = mechanical
loading_name = Mechanical
finite_strain = off
finite_rotation = offload = LS-DYNA/Explicithomogenization_model = Mori_Tanaka
hybrid_methodology = on
hybrid_quasistatic_strain_rate = 1.000000000000000e-006
hybrid_dynamic_strain_rate = 1.000000000000000e+002
hybrid_strain_range = 1.500000000000000e-001
hybrid_failure_strain_rate = 1.000000000000000e-006
FPGF_failure_indicator = FailureIndicator1
FPGF_failure_weight = 1.000000000000000e+000
FPGF_critical_fraction = 8.000000000000000e-001
FPGF_refinement = on
…
```

Linking DIGIMAT to LS-DYNA – update LS-DYNA model

Copy *.dyn material card into your input deck

```
*MAT_USER_DEFINED_MATERIAL_MODELS
$       MID        RO        MT       LMC       NHV    IORTHO     IBULK        IG
          1 1.67E-009        41         2        77         0         1         2
$     IVECT     IFAIL
          1         1
$     P1(K)     P2(G)
  4.46E+004 3.07E+004
```

Update *DATABASE_EXTENT_BINARY

```
*DATABASE_EXTENT_BINARY
$#    neiph     neips    maxint    strflg    sigflg    epsflg    rltflg    engflg
          0        77        12         1         1         1         1         1
$#   cmpflg    ieverp    beamip     dcomp      shge     stssz    n3thdt   ialemat
          0         0         0         1         1         1         2         0
```

Use a *KEYWORD_ID

Rename *.mat File into *41.mat – File

Define the shell section by computing the stiffness of every layer as function of the position of the layers in Moldflow:

```
*PART_COMPOSITE
$# title
Example
$#      pid    elform      shrf      nloc     marea      hgid    adpopt  ithelfrm
          2         2  0.833330     0.000     0.000         1         0         0
$#     mid1    thick1        b1   ithid1      mid2    thick2        b2    ithid2
          1  0.180000     0.000         0         1  0.213000     0.000         0
          1  0.241500     0.000         0         1  0.267000     0.000         0
          1  0.289500     0.000         0         1  0.309000     0.000         0
          1  0.309000     0.000         0         1  0.289500     0.000         0
          1  0.267000     0.000         0         1  0.241500     0.000         0
          1  0.213000     0.000         0         1  0.180000     0.000         0
```

Linking DIGIMAT to LS-DYNA – update LS-DYNA model

.key file

LS-DYNA Input Deck *.key - File

```
*KEYWORD_ID
DIGIMATinfo
*MAT_USER_DEFINED_MATERIAL_MODELS
$       MID        RO        MT       LMC       NHV    IORTHO     IBULK        IG
          1  1.67E-009       41         2        77         0         1         2
$     IVECT     IFAIL
          1         1
$     P1(K)     P2(G)
  4.46E+004 3.07E+004
*DATABASE_EXTENT_BINARY
$#    neiph     neips    maxint    strflg    sigflg    epsflg    rltflg    engflg
          0        77        12         1         1         1         1         1
$#   cmpflg    ieverp    beamip     dcomp      shge     stssz    n3thdt   ialemat
*SECTION_SHELL
$#      sid    elform      shrf       nip
```

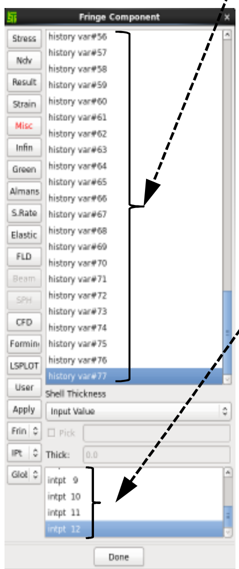
DIGIMAT DIGIMATinfo41.mat - File

```
name = Fibers
type = elastic
density = 2.500000000000000e-009
Young = 7.500000000000000e+004
Poisson = 2.200000000000000e-001

name = Matrix
type = J2_plasticity
density = 1.310000000000000e-009
consistent_tangent = on
Young = 2.430000000000000e+003
Poisson = 4.000000000000000e-001
yield_stress = 2.000000000000000e+001

MICROSTRUCTURE
name = GFRP
phase = Matrix
phase = Fibers
```

.mat file

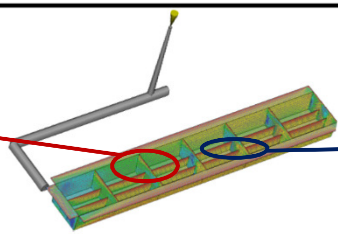


DIGIMAT DIGIMATinfo.dyn - File

.dyn file

```
$ history var# 1 : E11_macro - Average macro 11-strain
…
$ history var# 40 : C1111_Matrix - Average Matrix 1111-stiffness component
…
$ history var# 77 : S13_Fibers - Average Fibers 13-Cauchy stress
```

0.92	0.04	-0.01
	0.07	0
SYM		0.01



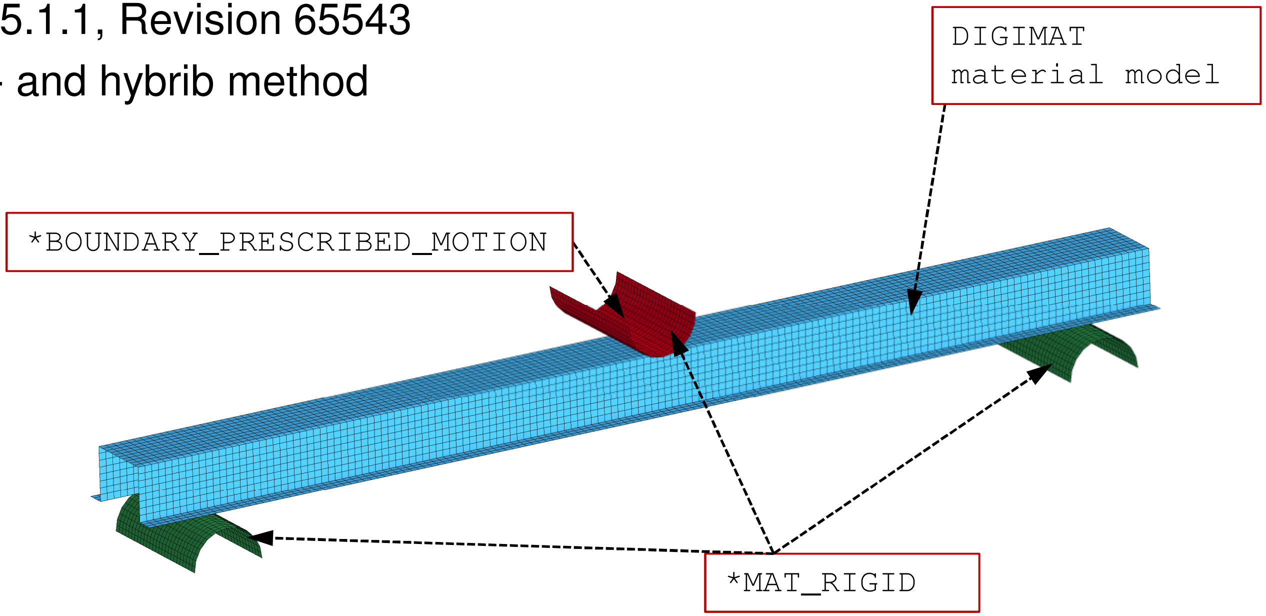
0.50	0.05	-0.01
	0.48	-0.01
SYM		0.02

.dof file

Linking DIGIMAT to LS-DYNA – Test example

Test example

- Classical three point bending test
- Results: nodal displacement at impactor, contact force at supporters
- Shell elements ETYP = 2, 4800 elements using DIGIMAT-material, 12 IP over the thickness (*PART_COMPOSITE)
- Calculation parameter: 0.2 sec., dt2ms: 4.5E-07
- LS-DYNA mpp971s, R5.1.1, Revision 65543
- Calculation with micro- and hybrib method



Linking DIGIMAT to LS-DYNA – Test example

- Four cores used
- LS-DYNA mpp971s, R5.1.1, Revision 65543
- Calculation parameter: 0.2 sec., dt2ms: 4.5E-07

Standard LS-DYNA Material

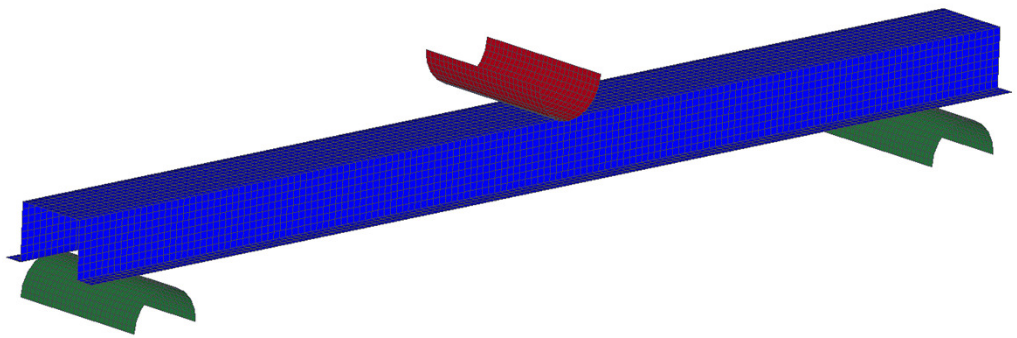
- Calculation time: 5h 15min

HYBRID – results:

- Calculation time: 5h 15min

MICRO – results:

- Calculation time: ~52h 40min

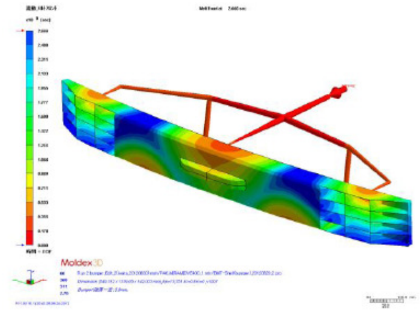


Linking DIGIMAT to LS-DYNA – full vehilce testing

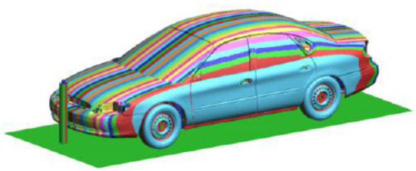
JSOL CORPORATION

Full vehicle System Level

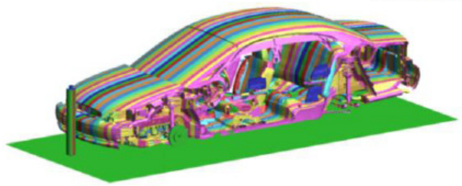
- ✓ **Pedestrian safety**
  - Bumper beam



Elements	3.1 Mio
Ave. elem size	5.0 [mm]
Min. time step	0.25 [µsec]
DIGIMAT	0.84% (26.000)



10 domains have no DIGIMAT elements



DIGIMAT elements in 22 domains

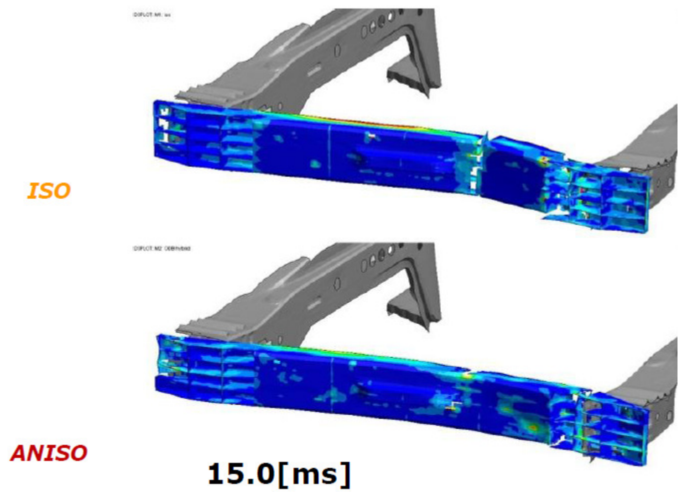
Linking DIGIMAT to LS-DYNA – full vehilce testing

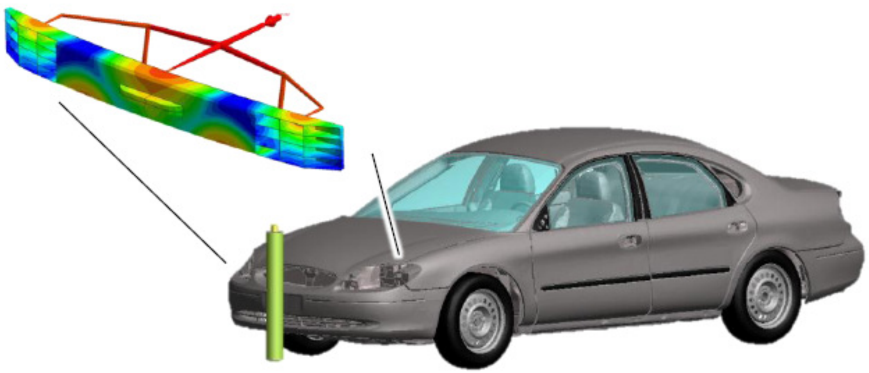
JSOL CORPORATION

NTT DATA

Full vehicle System Level

- ✓ **Acceptable increase of calculation time**
  - 9 →14 hours on 32 cores
  - Only 8 hours on 64 cores
- ✓ **Loss in efficiency for ISOTROPIC**
  - On 64 cores
  - Overhead of communication





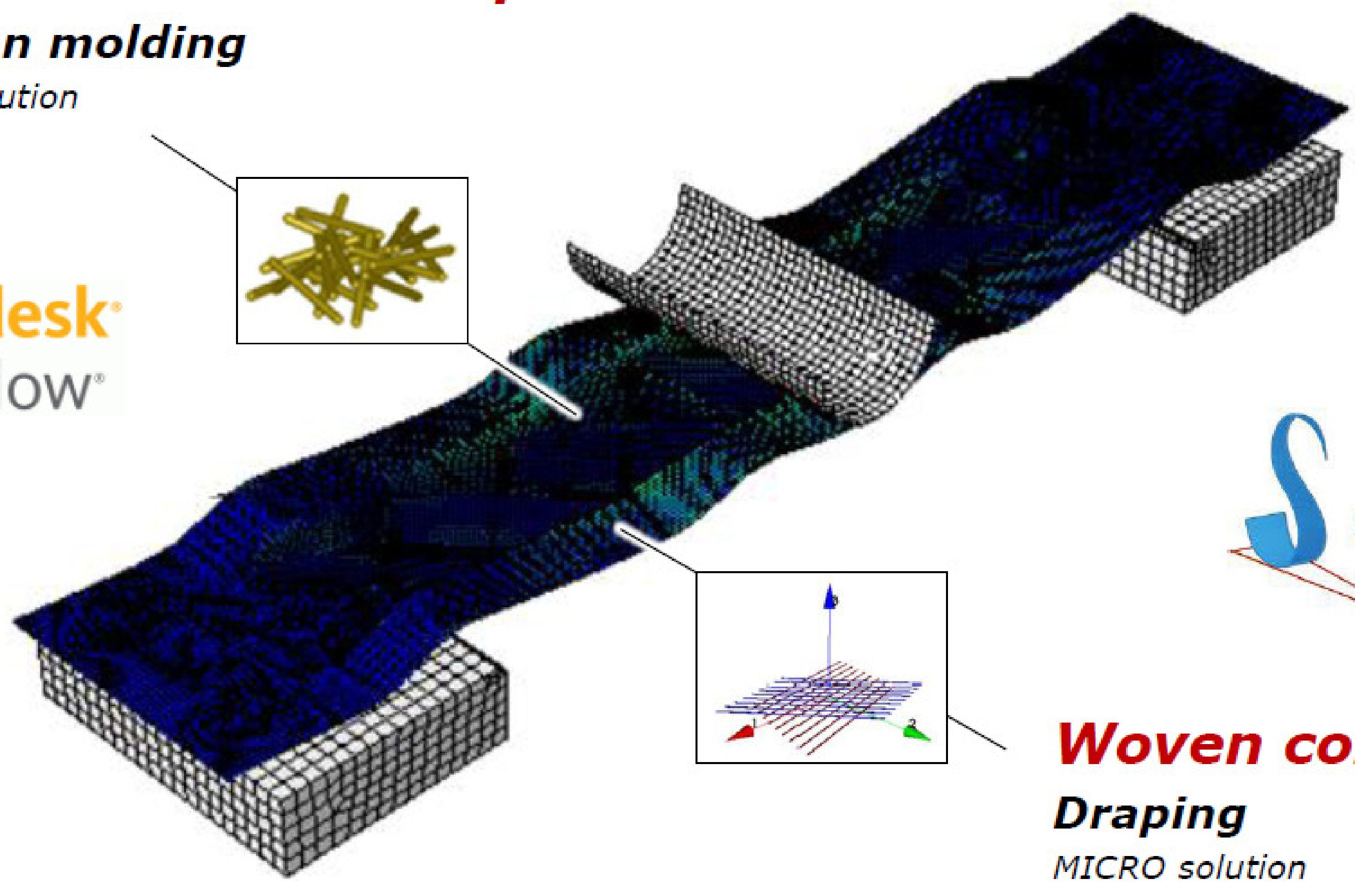
	16 cores	32 cores	64 cores
ISOTROPIC (improved)	17h 59min	9h 17min	10h 00min
HYBRID (default)		42h 31min	
HYBRID (improved)		14h 16min	
HYBRID (optimized)	26h 37min	12h 05min	8h 15min
Micro (improved)		152h 51min	

Linking DIGIMAT to LS-DYNA – woven composites

Short fiber reinforced plastics

Injection molding

HYBRID solution

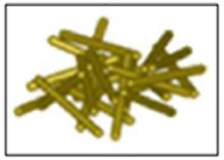


Woven composite

Draping

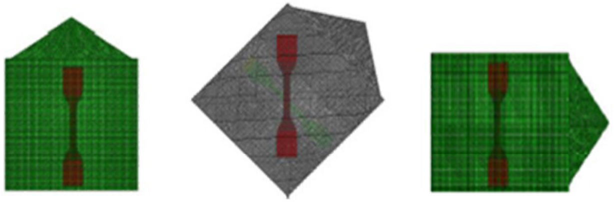
MICRO solution

Linking DIGIMAT to LS-DYNA – woven composites

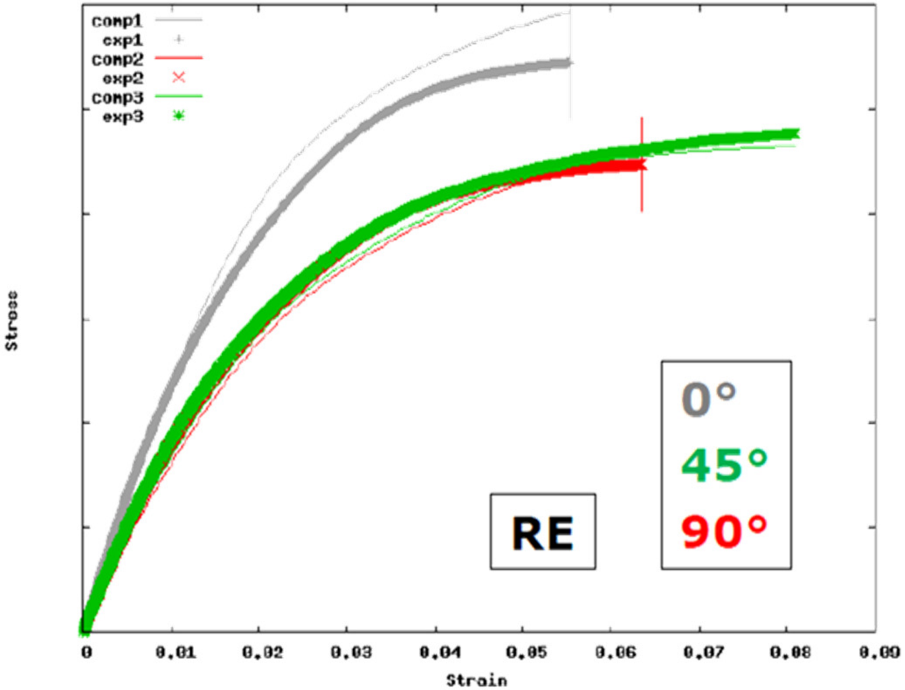


Overmolded Beam

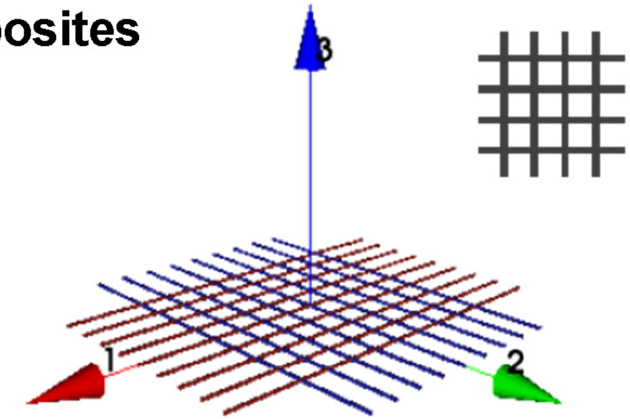
✓ Short fiber reinforced plastics



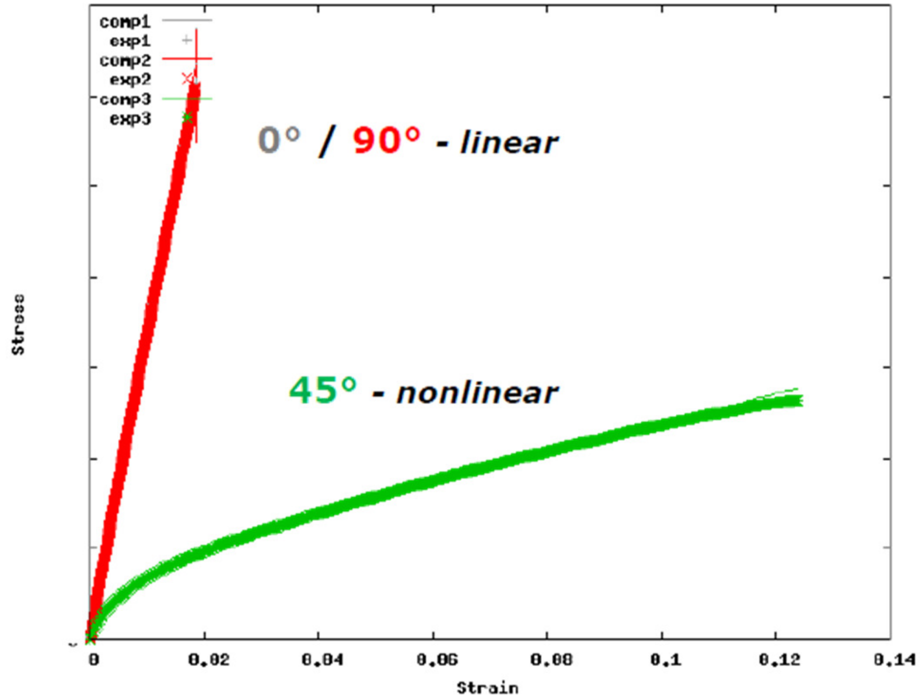
- Reverse engineering
  - Anisotropic
    - » From plate
  - Elastoplastic
  - Global fit
    - » 0°
    - » 45°
    - » 90°



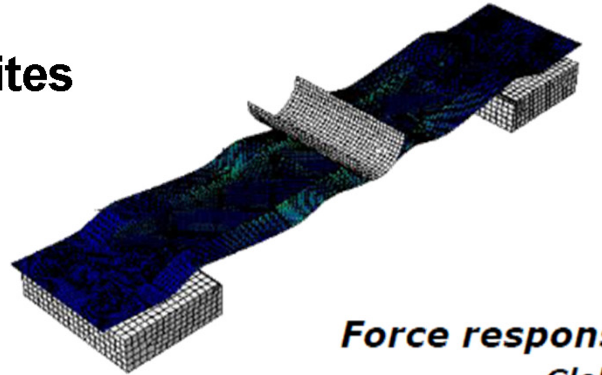
Linking DIGIMAT to LS-DYNA – woven composites



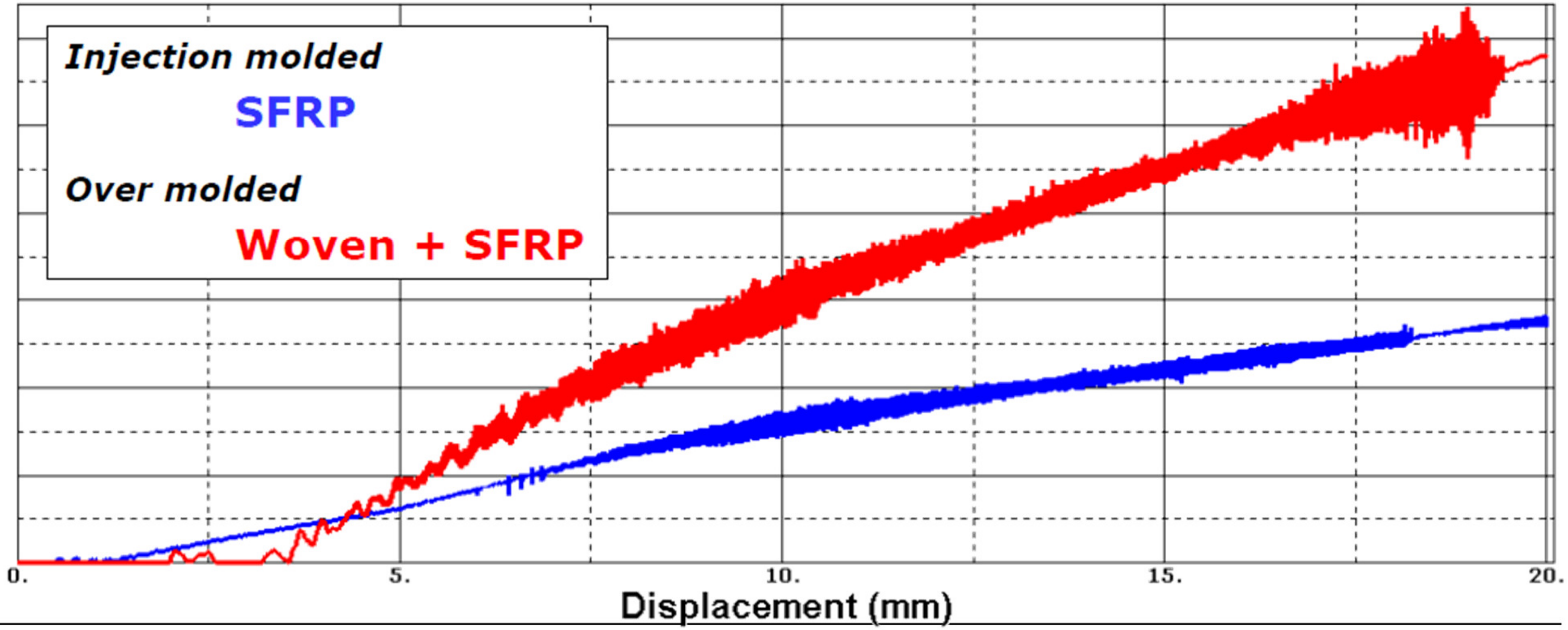
- **Overmolded Beam**
  - ✓ Woven composite
    - Measurements
      - Anisotropic
        - » From specimen
      - Elastoplastic
      - Global fit
        - » 0°
        - » 45°
        - » 90°



Linking DIGIMAT to LS-DYNA – woven composites

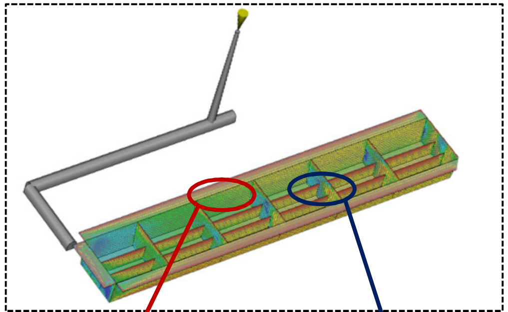


- **Overmolded Beam**
  - ✓ Coupled analysis
    - Injection molded vs. Over molded beam



Micro – Macro Modeling: Linking DIGIMAT with LS-DYNA

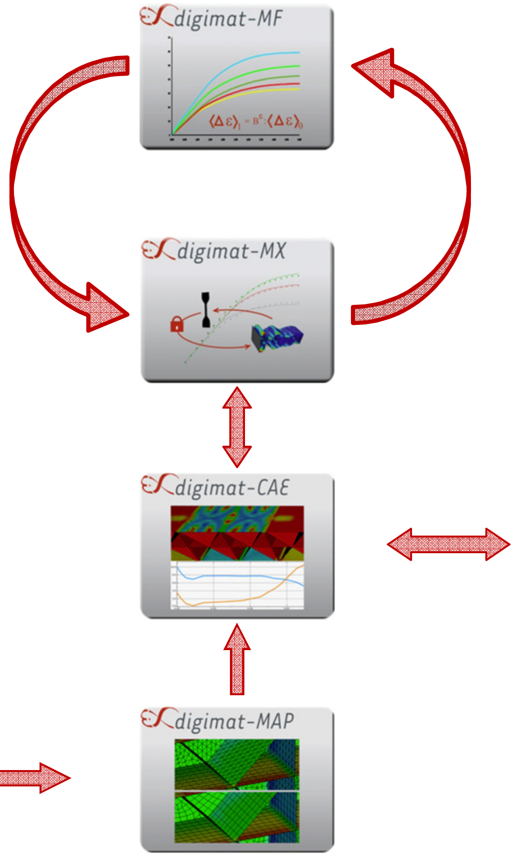
injection molding simulation



0.92	0.04	-0.01
	0.07	0
SYM		0.01

0.50	0.05	-0.01
	0.48	-0.01
SYM		0.02

different fiber orientation tensors

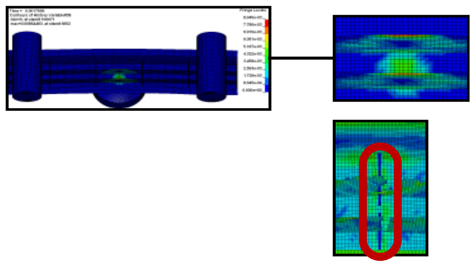


	LS-Dyna
Shell	1 (Hughes–Liu), 2 (Belytschko-Tsay), 4 (Triangular Shell), 6 (S/R Hughes–Liu), 16 (Fully integrated) -> Not for triangular elements
Solid	1 (Constant Stress), 2 (S/R Solid), 3 (Quadratic 8 nodes), 4 (S/R Tetrahedron), 10 (1pt Tetrahedron)

LSTC Livermore Software Technology Corp.

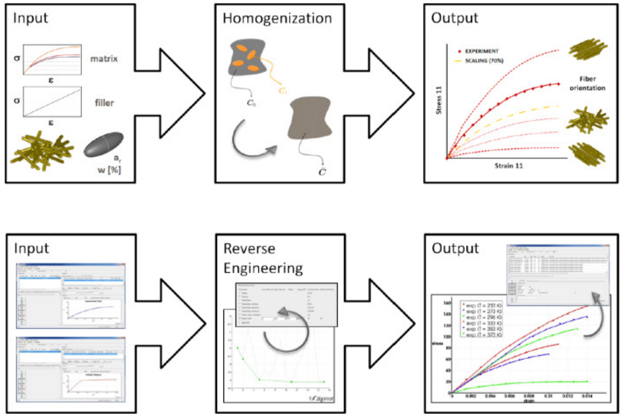
DYNA MORE

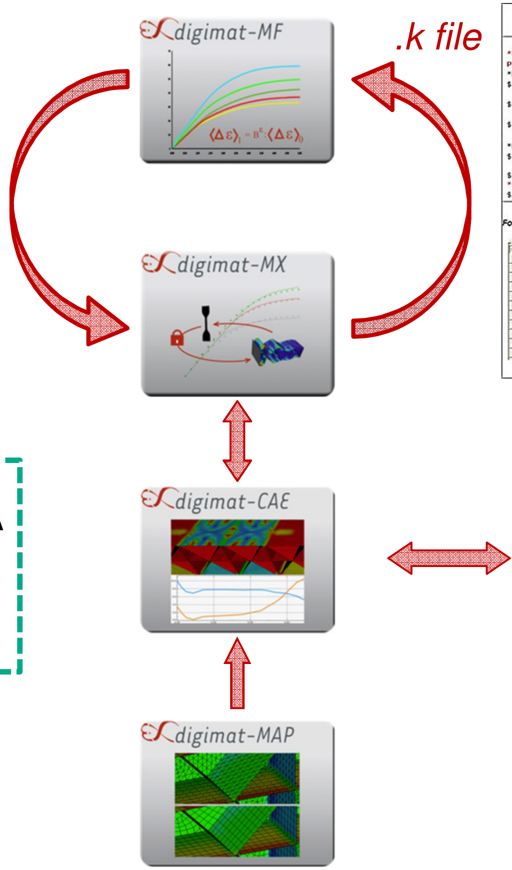
LS-DYNA

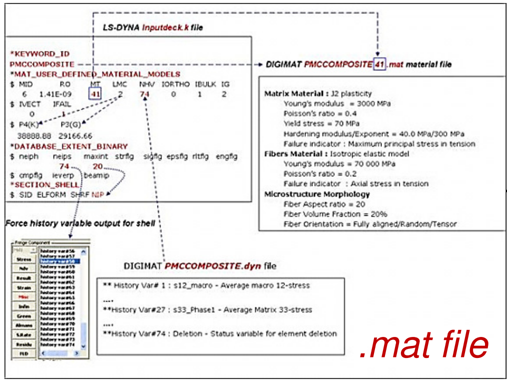


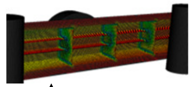
[Dr. J. Seyfarth: e-Xstream]

Micro – Macro Modeling: Linking DIGIMAT with LS-DYNA









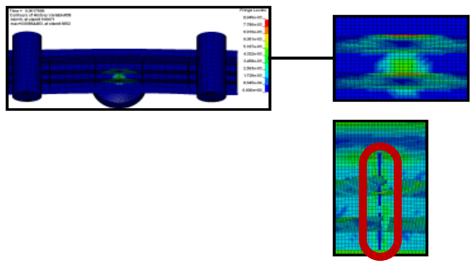
.dof file

coupling to LS-DYNA

implicit & explicit

LS-DYNA

Platform		Digimat to LS-DYNA (implicit & explicit)	
x86 32 bits	Windows XP, Vista, 7	Yes[5]	No
x86 64 bits	Windows XP, Vista, 7	Yes	Yes[4]
	Linux Suse 9 & 10, RedHat 4 & 5	Yes	Yes[2]



[Dr. J. Seyfarth: e-Xstream]

FIN