# VIRTUAL MATERIAL CHARACTERIZATION PROCESS FOR COMPOSITE MATERIALS: AN INDUSTRIAL SOLUTION

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**Abstract**

Detailed material modeling covering low continuum scales and scale-transition methods offers material and design engineers a virtual tool for the virtual material assessment and optimization, relaxing on the experimental testing efforts. This contribution demonstrates the different steps of a Virtual Material Characterization (VMC) process applied for the prediction of elastic properties of a real meso-scale composite geometry. The presented R&D results have been achieved as part of a running R&D program (*M3 MacroModelMat*), in which the meso-modeling framework will be extended with a key and unique aspect: non-linear and damage composite behavior to be used for attributes such as static strength, dynamic strength and NVH.

## 1. Introduction and motivation

There is a continuous strive to develop high-performance composites for different transportation industries, mainly driven by the advantages of lightweighting. In the pyramid approach (see Figure 1) applied for a wide range of applications, engineers apply an iterative hybrid test-simulation process that builds on the knowledge at the material-level studied at the stage of coupons. The largest number of tests is performed at this stage in order to generate material database covering design-critical aspects such as: stiffness, strength, manufacturing effects, variability and environmental effects.

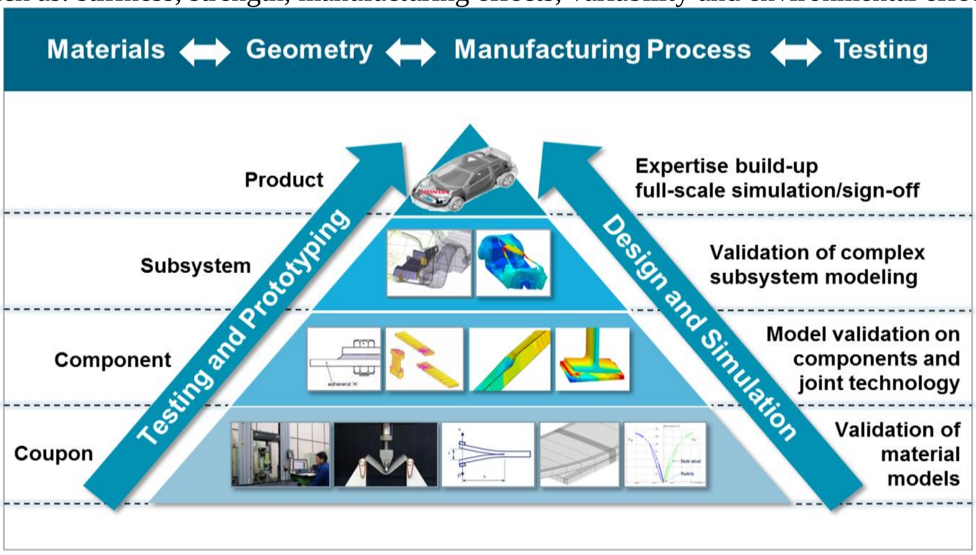


**Figure 1** Multi-stage design process: the pyramid approach

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In order to experimentally characterize the basic mechanical behavior of layered, continuum-fiber composites and obtain it's material properties/allowables, the minimum number of tests is equal to about 9 different coupons for each layup (without repetitions) – called *classical approach,* that treats a composite material as a homogenized laminate. The test effort explodes once design factors are considered such as damage tolerance or environmental aspects. For example for 2 design factors and 5 stacking sequence with 3 repetitions, the total effort is equal to 270 mechanical coupon tests.

It is possible to shift from such test-intensive CFRP development process towards a more efficient virtual product development by application of advanced FE modeling techniques. Continuum Damage Mechanics (CDM) models rely on a detailed representation of the non-linear progressive damage behavior of the orthotropic FRP material (still as homogeneous material) that require material parameters based on 13 coupon tests (without repetitions). The main difference with the *classical approach,* is that the material behavior is modelled ply-based separately representing intra- and inter-laminar behavior [1]. This *advanced approach* is a predictive solution for the FRP design challenge and reduces the test requirement for the aforementioned situation (2 design factors, 5 stacking sequence and 3 repetitions) to 78 coupon tests or to about 29% test effort, when compared to the *classical approach*.

Further relaxing on the test effort is possible by the application of multi-scale modeling concept. Staying at the continuum scales, this concept relies on detailed material modeling that goes down to micro-scale (or fiber-level) and sequentially builds knowledge in terms of material mechanical behavior towards the meso or yarn/bundle- and macro/application-scales (see Figure 2).

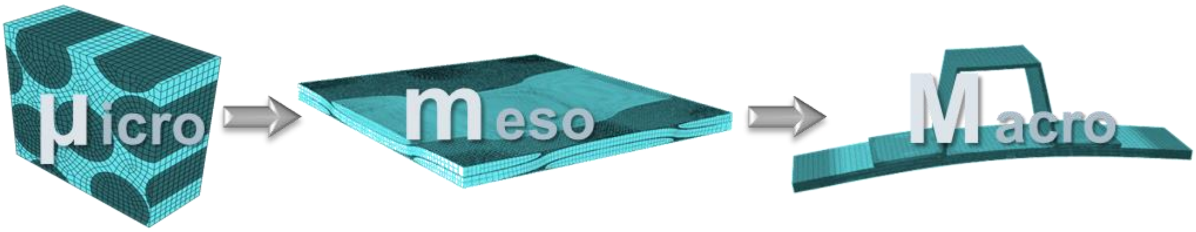


**Figure 2** Continuum material scales of a FRP material

Additional added value can be associated to multi-scale modeling in a virtual design process:

- virtual material testing and optimization in early design phase
- assessment of combined influence factors that cannot be tested (e.g. shearing and its impact on permeability)
- include manufacturing-related aspects that cannot be represented at macro-scale (defects such as porosity,…)

Siemens PLM Software, in collaboration with KU Leuven (Belgium), developed in the context of short/random fiber composites an efficient virtual solution for fatigue response that is based on multi-scale modeling and Mori-Tanaka homogenization [2]. The proposed technique enables an efficient SN-based durability assessment based on a minimal set of coupon tests.
As part of the Siemens PLM Software R&D strategy towards the complete end-to-end simulation of composite materials, in collaboration with UGent (Belgium) and KU Leuven (Belgium), further investments are planned in order to extend the industrialization of different multi-scale methodologies, resulting in a Virtual Material Characterization (VMC) Toolkit. This paper is a demonstrator of VMC functionalities applied on a realistic woven CFRP material. The objective is to illustrate the different steps of a VMC process that is validated for the elastic constants of the material in focus.

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## 2. The proposed workflow for the multi-scale modeling of continuous fiber-reinforced materials

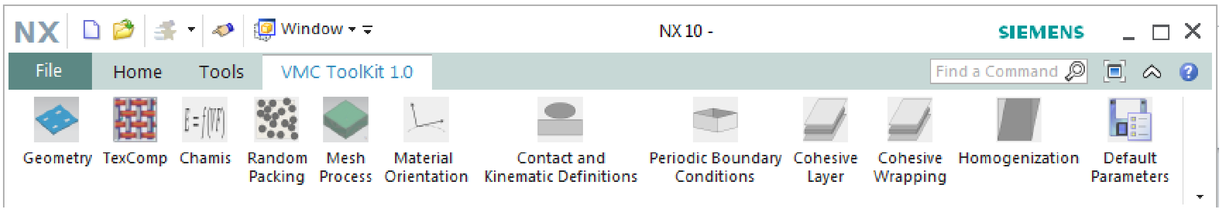


**Figure 3** VMC Toolkit covering different modeling steps of a multi-scale workflow

Proof-of-concept toolset is proposed (see Figure 3 for the functionality elements) that covers the following multi-scale methods applicable at different material scales:

**Micro-scale modeling:**
- Geometry engine: random-packing according to the article by Merlo et al. [3]
- Analytical homogenization: Chamis formulas [5]
- FE-based homogenization: see similar steps described for *meso-scale modeling*

**Meso-scale modeling:**
- Geometry engine: interfacing with *WiseTex* by KU Leuven [6,7]
- Analytical homogenization: integration of *TexComp* by KU Leuven [7]
- FE-based homogenization: integration of *ORAS* by UGent [8]:
  - Material orientation definition tool: accounts for the yarn crimp
  - Contact zone definition and kinematic definitions: functionality to cover the automatic creation of the surface groups between the yarns and the matrix material with option to avoid kinematic conflict problems due to common nodes in groups used for the PBC and for the contacts.
  - Periodic Boundary Condition (PBC) definition: collection of kinematic connections which ensure the periodicity of the model, while applying the strain-loading on the periodic unit cell [9]
  - Cohesive tools: allows the automatic definition of cohesive zones for damage propagation non-linear loading scenarios
  - Homogenization tool: automatic processing of the stress and strain fields into homogenized material properties

**Generic elements:**
- Streamlined meshing process: semi-automated multi-stage meshing process with control of the key parameters and tailored to bi-phase material cells allowing efficient quality meshes
- Material data management as part of a database enabling material traceability

In the following sub-sections, highlights are given on some functionality elements of the VMC process.

### 2.1. Micro-scale modeling

Alternative to the analytical homogenization (e.g. by Chamis formulas [5]), the FE-based micro-scale modeling is considered, that accounts for a realistic fiber-packing representation. Merlo et al. proposed a widely accepted and applied algorithm for the generation of random spatial distribution of fibres [3]. It was demonstrated by experimental comparison, that the algorithm is capable of capturing the random nature of the fiber distribution typical for the continuum fiber-reinforced composite materials [4]. Figure 4 shows an example of a micro-scale geometry generated based on the random-packing algorithm, which is periodic and ready to be submitted to a meshing process and the subsequent FE-based homogenization steps.

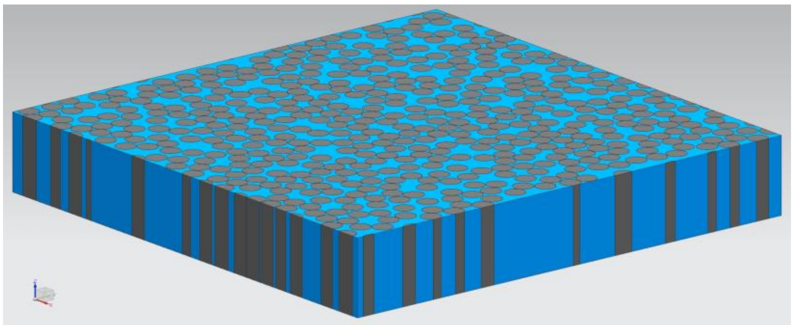

**Figure 4** Micro-scale model built by random-packing algorithm

### 2.2. Meso-scale modeling

Starting with a geometry generation of the unit cell, the interface to *WiseTex* allows the CAD translation of woven and NCF structures that are created with this geometry tool [6]. Figure 5 illustrates the different steps of reconstruction which are automatically applied during the import process of a *WiseTex* model, applicable for both orthogonal and non-orthogonal (sheared) yarn configurations.

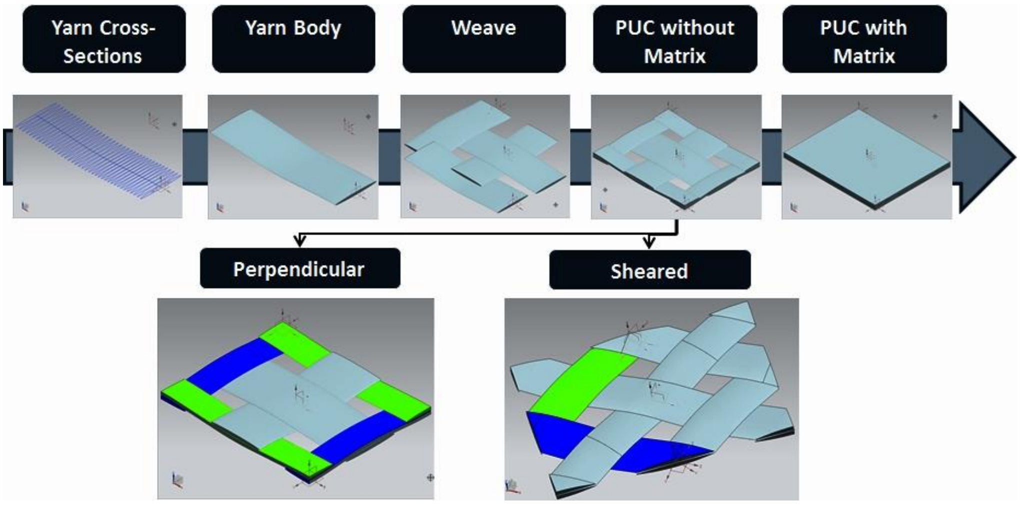


**Figure 5** Import mechanism of a woven reinforcement from WiseTex and its completion towards a Periodic Unit Cell (PUC) CAD model

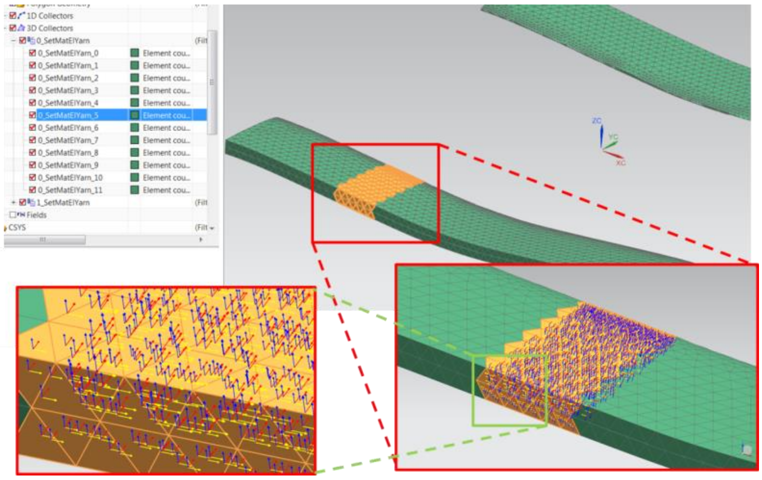

**Figure 6** Automatic local material orientation mapping by discretization of the yarns

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The geometry creation step is followed by a meshing process and is succeeded by different pre-processing steps of the PUC. The correct material mapping is a key step in the pre-processing that accounts for the local material orientation changes due to the yarn crimp. The proposed automatic tool efficiently creates different material groups along each yarn based on user-defined discretization (see Figure 6). The meso-modeling process is completed by interface or contact definition between the yarns and the surrounding matrix material – allowing also the study of non-linear interface behavior by the application of cohesive zones. Maintaining periodicity during the strain-based loading is achieved by the PBC tool (applicable also in case of non-symmetric meshes at the opposite faces of the PUC). The resulting unit cell may be submitted to an FE solver followed by the homogenization step. In this step, the homogeneous macro-scale material elastic constants are calculated by the volume-averaging technique applied on the stress-fields [8].

## 3. Application[1]

A woven material is chosen for the validation of the process that is used in automotive industry. The geometry (see meshed geometry in Figure 7) is reconstructed from X-ray tomography such that interpenetration and volume-fraction corrections can be avoided [10].

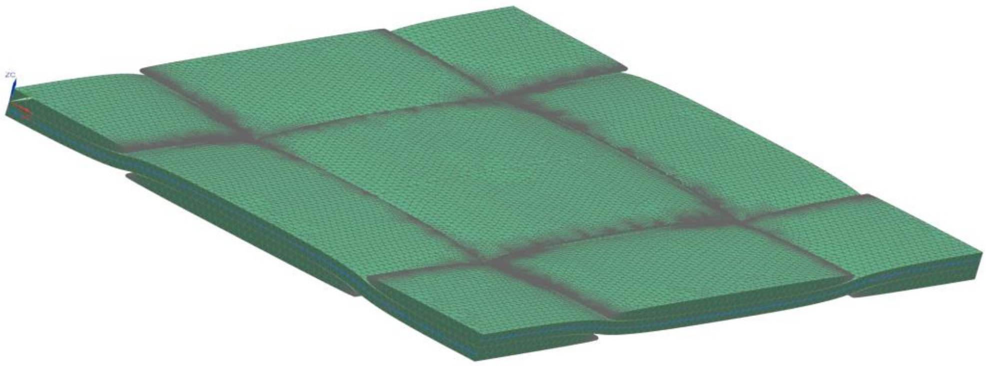

**Figure 7** Meshed geometry of the PUC (only yarns are shown)

The yarns are representing the impregnated material with transversely-isotropic behavior with properties obtained by micro-scale homogenization according to the Chamis formulas [5].
Relative comparison of the elastic properties between experimental measurements and predictions is shown in Table 1. Important to be noted that experimental material variability is not considered in this comparison and the numerical process has not been studied for the effect of different influence factors that can impact the results (e.g. mesh density). Furthermore, there is a certain degree of uncertainty in the predicted values the Poisson's coefficient $v_{12}$ and the shear modulus $G_{12}$ due to insufficient details available for the carbon fibers (the complete transverse-isotropic data) which have significant influence on these values.
It is important to note that the applied toolset allowed the complete meso-scale homogenization process on this use-case in the order of few 10's of minutes accounting for the user interactions during pre- and post-processing (excluding FE solver time).

**Table 1.** Comparison of elastic constants: experimental vs. predicted.

| Material data | $E_{11}$ (%) | $E_{22}$ (%) | $v_{12}$ (%) | $G_{12}$ (%) |
|---|---|---|---|---|
| Experimental | 100 | 100 | 100 | 100 |
| Predicted | 95.82 | 95.79 | 215.91 | 89.69 |

[1] Due to confidentiality reasons, absolute values of material data are not shown

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## 4. Conclusions

This paper is a short demonstration of a new industrial process targeted for the Virtual Material Characterization (VMC) of continuum-fiber reinforced materials. It is the first step towards a complete and efficient multi-scale simulation process for VMC, established as part of Siemens PLM Software. The main value of the VMC is in shifting material development and optimization from a test-based approach towards a virtual testing approach. The vision for this approach is to allow engineers material exploration and efficient translation of design requirements to material requirements in early design stages. Furthermore, detailed modeling at different continuum-scales allows the virtual testing of inherent material features (defects, imperfections) that are typically only experimentally assessed and are accounted for by safety factors or knock-down factors. Summing up the expected impact of the VMC in ligthtweight design: reduction of the design time due to more efficient material identification and optimization also allowing the systematic reduction of safety-factors by increased knowledge on material behavior.

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## References

[1] Michael Bruyneel, Jean-Pierre Delsemme, Philippe Jetteur, Cédric Lequesne, Benoit Magneville, Louis Soppelsa, Scott McDougall, Tadashi Naito, Yuta Urushiyama, Damage Analysis of Laminated Composites with SAMCEF: Validation on Industrial Applications, American Society for Composites 30th technical Conference, Michigan State University, USA, Sept 28-30, 2015.
[2] Atul Jain, Jose M. Veas, Stefan Straesser, Wim Van Paepegem, Ignaas Verpoest, Stepan V. Lomov, The Master SN curve approach – A hybrid multi-scale fatigue simulation of short fiber reinforced composites, Composites Part A: Applied Science and Manufacturing, Available online 11 December 2015.
[3] A. R. Melro, P. P. Camanho, S. T. Pinho, Generation of random distribution of fibres in long-fibre reinforced composites, Composites Science and Technology 68 (2008) 2092–2102.
[4] Romanov, V., S.V. Lomov, Y. Swolfs, S. Orlova, L. Gorbatikh, and I. Verpoest, Statistical analysis of real and simulated fibre arrangements in unidirectional composites. Composites Science and Technology, 2013. 87: 126-134
[5] Chamis, C., Mechanics of Composite Materials: Past, Present, and Future, Journal of Composites, Technology and Research, Vol. 11, No. 1(March 1989), pp. 3-14.
[6] Ignaas Verpoest, Stepan V. Lomov, Virtual textile composites software WiseTex: Integration with micro-mechanical, permeability and structural analysis, Composites Science and Technology, Volume 65, Issues 15–16, December 2005, Pages 2563-2574.
[7] WiseTex software, KU Leuven, MTM Department: https://www.mtm.kuleuven.be/Onderzoek/Composites/software/wisetex
[8] S. Jacques, Development of a framework for the construction of meso-scale finite element models of textile composites. Ghent University Faculty of Engineering and Architecture, PhD Thesis, 2014.
[9] S. Jacques, Development of a Framework for the Construction of Meso-Scale Finite Element Models of Textile Composites, Ghent University. Faculty of Engineering and Architecture (2014), ISBN 978-90-8578-735-8.
[10] R.D.B. Sevenois, D. Garos, F.A. Gilabert, W. Van Paepegem, Avoiding interpenetrations and fibre volume fraction corrections in representative unit cells for textile composites through advanced geometry generation, ECCM17 - 17th European Conference on Composite Materials, Munich, Germany, 26-30th June 2016.

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