VIRTUAL CHARACTERIZATION OF SHORT CHOPPED FIBER REINFORCED PLASTICS BEHAVIORS

Sylvain Calmels, Moncef Salmi
e-Xstream Engineering

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Investigating the behavior of nonlinear anisotropic multi-phase materials comes with challenges: a significant increase in physical testing is required to understand the complex mechanisms appearing at different scales and their effect on the material's macroscopic behavior. Moreover, the current economical context pushes every company to optimize their organization in order to reduce R&D costs as much as possible. While the pressure of reducing R&D costs, including material characterization campaigns, is growing, partially replacing physical testing by virtual testing can obviously provide a huge benefit.

Short fiber reinforced plastic material behavior is complex to identify due to the intrinsic multi-phase microstructure. On one hand, the fiber orientation distribution is directly driven by the manufacturing process, resulting in a heterogeneous organization through a component. This induces a large range of potential local nonlinear anisotropic behaviors throughout a given part which must be used in FEA. On the other hand, the different resins show very different behaviors. In addition, for each of them, the behavior can vary significantly depending on the temperature and relative humidity. Using a powerful combination of full field homogenization and mean field homogenization techniques can help in the virtual characterization of those complex behaviors starting from a reduced initial set of physical test data. Appropriate methods allow us to identify, for example, nonlinear and anisotropic stiffness, failure and post failure behaviors for different fiber orientations and fiber volume fractions, but also strain rates or temperatures.

The present paper will demonstrate how the existing multi-scale material modeling techniques can help to enrich, quickly and easily, a material model database, or to decrease dramatically the cost and time required to characterize the behavior of short fiber reinforced plastic materials.

Challenge for characterization of SFRP materials

Various mechanical behaviors to measure for various types of performances

Prior to building a material model in a finite element model for a given SFRP grade from a given material supplier, the material must be tested at sample level in order to measure its specific behaviors. Of course, depending on the targeted performance, the required data are different. If we consider the usual needs regarding the mechanical performance of SFRP made components in the automotive industry, they can be basically summarized like shown on table 1:

Table I: Typical mechanical behaviors for SFRP function of performance

SFRP Mechanical Behaviors					
Static	**Crash**	**Fatigue**	**Creep**	**NVH**	**Thermomech.**
Elasticity	Rate dependent Stiffness	Elasticity	Visco-elasticity	Frequency dependent stiffness	Thermo-elasticity
Plasticity	Rate dependent plasticity	R ratio dependent fatigue failure	Visco-plasticity	Frequency dependent damping	Thermo-plasticity
Failure	Rate dependent failure				Thermo-dependent failure
	Rate dependent post failure				CTE

In addition, all these behaviors show dependencies on the environmental conditions, the loading type and to fiber orientations. These must also be considered when setting the testing campaigns. Table 2 below summarizes them:

Table 2: SFRP behaviors dependencies to environment conditions, loading types and microstructure

Behaviors Dependencies for 1 grade		
Environment	**Loading**	**Microstructure**
Temperature	Tension	Fiber Orientation
Relative Humidity	Compression	
	Shear	
	Multi-axial	

Hence, when an automotive OEM or a Tier1 needs to design a structure made of an SFRP grade, the characterization of its behaviors and associated dependencies requires a significant amount of tests to be performed, especially if several performances must be covered during the development phase.

In addition, we have to also consider the potential variabilities brought by the material constituents. One material grade for short fiber reinforced plastic can be considered as a combination of 4 parameters listed on table 3 below.

Table 3: Material selection parameters for SFRP

SFRP grade parameters	
Matrix	**Filler**
Resin Material	Fiber Material
	Fiber Mass Fraction
	Fiber Aspect Ratio

Test matrix examples

Considering one material grade, meaning a combination of resin material, fiber material, fiber mass fraction and fiber aspect ratio, we will identify what the test matrix to be performed in order to characterize all behaviors listed in the previous paragraph is.

Table 4 below summarizes a typical test matrix to be performed for one set of environmental conditions (Temperature; Relative Humidity) for one material grade. Measurements of compressive behaviors still being a challenge today, there is no real existing standard at this level, therefore, they won't be considered here, in a first approach.

Table 4: Typical test matrix to cover measurement needs for the main performances

	SFRP Mechanical Behaviors					
	Static	**Crash**	**Fatigue**	**Creep**	**NVH**	**Thermomech.**
Loading	Tensile	Static + Dynamic Tensile	Static + Cyclical fatigue	Static + fixed load creep	Static + DMA	Static + TMA
Fiber orientations	0°, 45°, 90°	0°, 45°, 90°	0°, 30°, 90°	0°, 90°	0°, 90°	0°, 90°
Other setting	Quasi static	3 strain rates from 1e-01/s to 100/s	3 R ratios from -1 to 0	Quasi static for 3 load levels	Sweep T from -40 to 200°C ; 4 frequencies from 0.1Hz to 100Hz	4 temperatures from -50°C to 150°C
Replicates	5	5	5	5	5	5
Total amount of tests	15	15 (Static) + 45 = 60	15 (Static) + 45 = 60	15 (Static) + 30 = 45	15 (Static) + 40 = 55	15 (Static) + 40 = 55

The amount of typical tests required to characterize a material grade is then significant. This induces a large effort in terms of cost and time. The point is that this is often enlarged by the numerous possible material grades available in the market. Even for the same material supplier, at fixed resin material, fiber material and fiber length, it’s always useful to evaluate the performance of 2 to 3 different mass fraction of fibers in a component’s design. This means the previous test matrix is directly multiplied by 2 or 3. Even considering only static and crash needs for example, this means one can need from 60 to 180 tests to be performed. If the complete test matrix is taken into account, the total amount of tests would go from 215 tests for 1 grade to 645 for just 3 different mass fractions for the same type of resin and fiber.

This very large choice of SFRP materials available on the market has brought a large increase in terms of testing compared to previous situations with metals. In addition, these materials are showing more complex behaviors which requires even more testing. This is notably due to their anisotropic behaviors linked to the local fiber orientations resulting from the manufacturing process. Unfortunately, rare are the companies which are able to handle this complete test campaign. The main reasons are cost, resources and time availabilities. Consequently, design teams are obliged to rely on strong and inaccurate assumptions regarding the material behavior. They are also obliged to reduce their design space by ignoring very important parameters such as the fiber mass fraction. Strong assumptions mean a high risk of inaccuracy in simulations and long trial & error loops during design development phases. Reduction of the available design space will drive to overdesign, hence a potential loss in terms of light-weighting.

Therefore, there is a need for a solution which could help to reduce the amount of required experimental tests for SFRP materials. But this should still provide accurate material data to feed design teams with accurate inputs. This would represent a breakthrough in the design methods to be applied for SFRP components.

Virtual characterization of SFRP materials behaviors

Multi-scale modeling techniques to capture microstructure dependent behaviors

SFRP materials are well known to provide anisotropic behavior driven by their microstructure, microstructure itself resulting from the injection molding process. Whatever the need is to measure stiffness, plasticity, failure, damping or even thermal expansion, this fact must be taken into account. During the past years, using multi-scale modeling techniques in order to capture these specificities of multi-phase materials like SFRPs became a standard. Digimat has been the first commercial product thirteen years ago to propose the use of a multi-scale modeling technique for industrial applications. Nowadays this platform is proposing two different, and complementary, methods of multi-scale homogenization which allows us to build workflows dedicated to such problems as exposed previously.

Mean-Field Homogenization

As SFRP material properties depend on the material microstructure including fiber amount and orientation, they are adequately modeled from micromechanics. In particular, mean-field homogenization combines the properties of the underlying constituents of a multi-phase material so that the original heterogeneous material is represented by an equivalent homogeneous one. Implemented in the Digimat software, this technology has proven efficiency for a broad range of materials. For SFRP, the matrix material can be modeled using various types of behavior depending on the targeted performance. Typical usages are

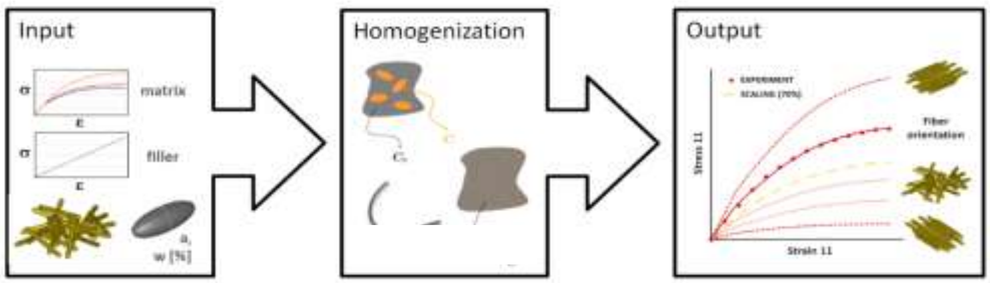
- isotropic elastic for fatigue
- isotropic elastoplastic for Statics

- isotropic elastic or viscoelastic for NVH
- isotropic viscoelastic or elastoviscoplastic for creep
- isotropic elastoviscoplastic for Crash
- isotropic thermoelastic or thermoelastoviscoplastic for thermomechanics.

The fiber material is usually modelled as isotropic elastic or transversely isotropic elastic depending on the filler's material and accounts for the actual fiber volume fraction and aspect ratio.

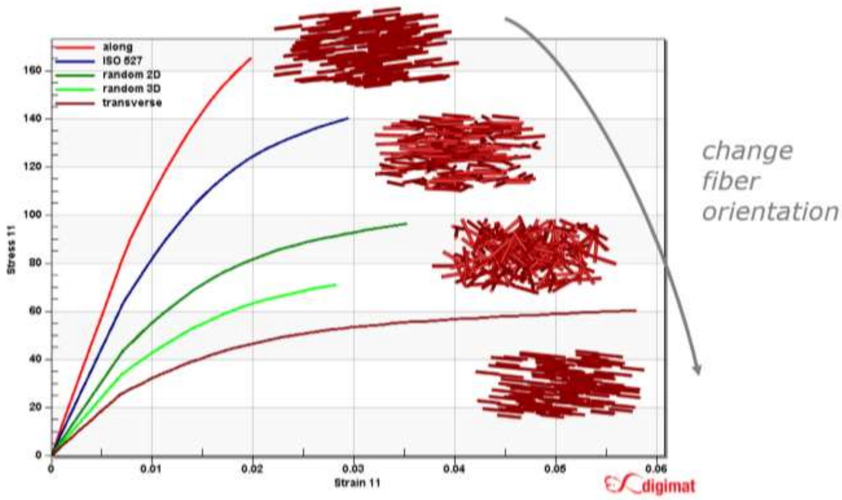
Mean-field homogenization provides a means to investigate the origin of the experimental variability of composite properties. In particular, it reveals their sensitivity to micromechanical parameters like fiber orientations, fiber mass fraction and aspect ratio.

Figure 1: Mean Field homogenization predict composite level behaviors from constituent properties



Like shown on figure 2, the typical application of mean field homogenization technique is to build a material model capable of capturing the influence of local fiber orientations onto the SFRP material behavior based on an initial set of experimental data measured at 0°, 90° and ideally also 45°.

Figure 2: Mean Field homogenization predict vaying stiffness and failure behavior function of local fiber orientation

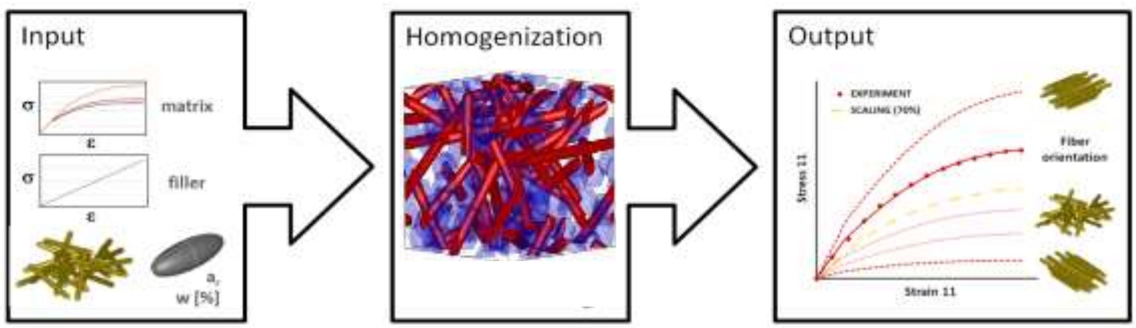


Full-Field Homogenization

The basis of a full field homogenization technique is similar to mean field homogenization: the aim is still to predict composite level behaviors based on the definition of the materials constituent properties and the local microstructure. However, the methodology is different.

Full-field homogenization aims at predicting the macro behaviors based on micro ones by building a finite element model of the Representative Volume Element (RVE), applying required boundary conditions and loading it in order to run an FEA directly on the RVE model as shown in the middle box of figure 3 below. Hence the fibers, their shape and arrangement within the matrix material are explicitly modelled. This helps to describe a detailed microstructure in a much finer way than by mean-field homogenization. The typical output from such calculations is a distribution of stresses and strains among the finite elements of the matrix, the fibers and possibly interface elements in between. Notably to treat failure analysis, this method helps to identify, much more precisely, the per-phase failure criteria vs. mean field homogenization.

Figure 3: Full Field homogenization predict composite level behaviors from constituent properties



Application to the virtual characterization of nonlinear stiffness

As a first level of application, it is proposed to apply a combination of the 2 previously proposed methods to predict the nonlinear stiffness behavior of a PPGF40 material starting from tensile test data for a PPGF20 from the same material supplier:

- Data available for material model creation : quasi static tensile tests on coupons 0° and 90° for a PPGF20 from a material supplier named MS1
- Data available for validation of the method : quasi static tensile tests on coupons 0° and 9° for PPGF40 from MS1
- Target : virtually perform tensile tests on coupons 0° and 90° for PPGF40 from MS1
- Criteria of acceptance : comparison between virtual test results and quasi static tensile tests data from MS1

The demonstration presented in this paper will focus on the prediction of the nonlinear stiffness which is a prerequisite to a next step, which will address failure. This demonstration will go through the following steps:

1. Create a mean field homogenization model for PPGF20 capable of capturing the effect of fiber orientations on the material's nonlinear stiffness
    - Identify resin property by targeting stress/strain curves from experimental data on coupons cut from injected plaques at 0° and 90°
    - Generate virtual tensile data for perfectly aligned fiber orientation tensor (1,0,0)
2. Create a RVE model using full field homogenization for PPGF20 for a perfectly aligned fiber

orientation tensor (1,0,0)

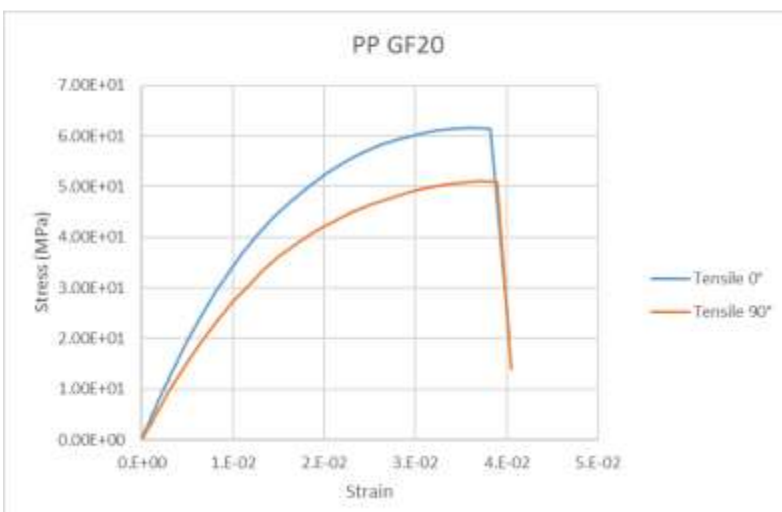
- Create and mesh geometry for a perfectly aligned PPGF20 RVE
- Use initially resin property identified in step 1
- Refine resin property and fiber aspect ratio based on comparison with virtual tensile data (1,0,0) generated in step 1

3. Create a RVE model using full field homogenization for PPGF40 for perfectly aligned fiber orientation tensor (1,0,0)
   - Create and mesh geometry for a perfectly aligned PPGF40 RVE
   - Apply refined properties for resin identified in Step 2
   - Generate 0° and 90° virtual tensile data for perfectly aligned fiber orientation tensor (1,0,0)
4. Create a mean field homogenization model for PPGF40 capable of capturing the effect of fiber orientations on the material's nonlinear stiffness
   - Identify resin property by targeting stress/strain curves from 0° & 90° virtual data generated in step 3 for perfectly aligned fiber orientation tensor (1,0,0)
   - Change fiber orientation tensor for appropriate one considering coupons cut from plaques
   - Generate virtual tensile data for 0° and 90° loading direction considering fiber orientation tensor on coupons cut from plaques
   - Compare virtual data with experimental data

Step 1: Create a mean field homogenization model for PPGF20

The target of step one is to properly identify the resin properties and the appropriate microstructure parameters in order to accurately capture the anisotropic nonlinear stiffness visible on tensile data 0° & 90° shown on figure 4.

Figure 4: Experimental tensile data on coupon 0° & 90° for PPGF20



Such tests are performed on coupons cut from plaques. The microstructure on such coupons is well known as showing a skin/core effect with quite a significantly preferred orientation tensor driven by the material flow during the injection process. But this can vary slightly from 1 coupon to another depending on the shape of the plaque and, of course, the materials. That's why in this creation process, an initial microstructure is assumed and is then slightly adjusted in order to accurately capture the anisotropy shown by the experimental curves.

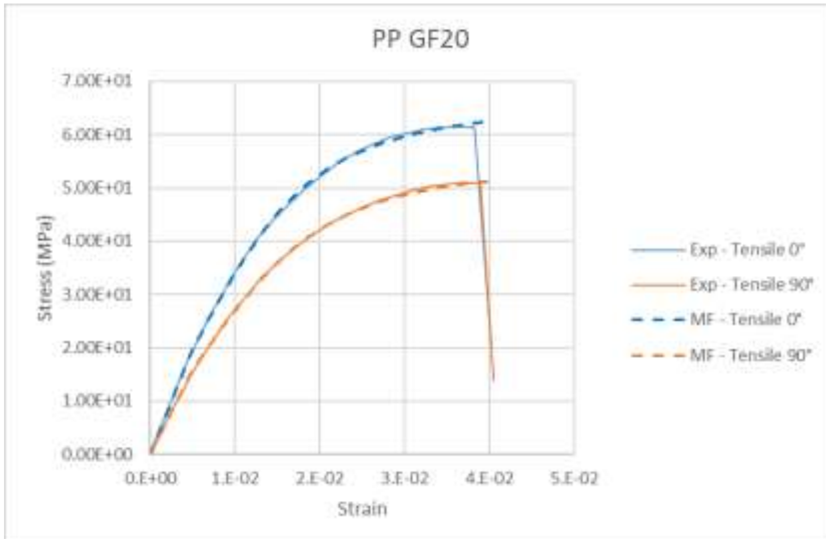
The final parameters of the material model for this PPGF20 are summarized on table 5 below:

Table 5: Identified resin property and microstructure for creation of PPGF20 material model

Material parameters	PP Resin	Glass fiber	Microstructure parameters	Skin	Core
Density (T/mm3)	9.1e-10	2.54e-09	**Proportion of thickness**	75%	25%
Young's modulus (MPa)	2000	72000	**A11**	0.75	0.23
Poisson's ratio	0.3	0.22	**A22**	0.23	0.75
Yield stress (MPa)	12		**A33**	0.02	0.02
Hardening modulus (MPa)	27.5		**Aspect ratio**	22	
Hardening exponent	165				
Hardening modulus 2 (MPa)	25				

By using these parameters, the corresponding material model is perfectly capturing the measured behaviors. Figure 5 is showing the comparison between stress/strain curves from the model and the experimental test.

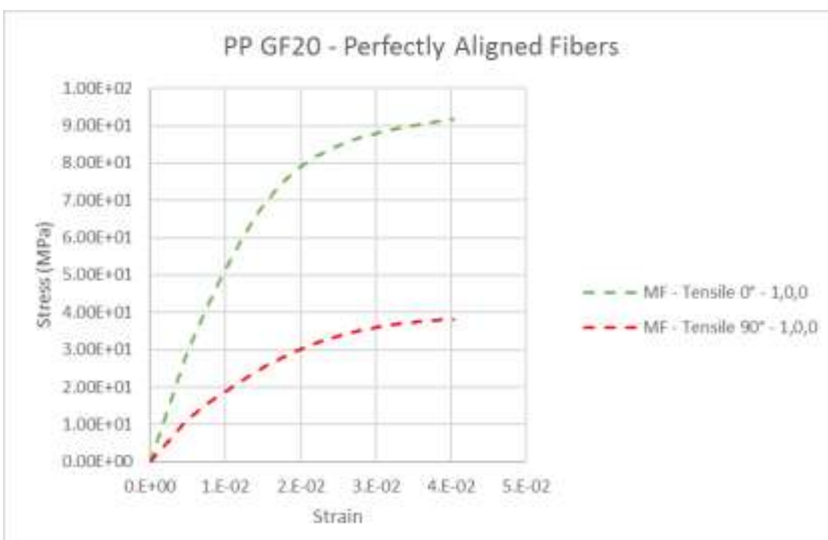
Figure 5: Mean Field Homogenization model captures accurately the anisotropic nonlinear stiffness from measurements for PPGF20



Once the mean field homogenization model is created, it is possible to virtually predict the behavior of the material for a different fiber orientation tensor. Figure 6 below shows the prediction of 0° and 90° tensile behaviors of the PPGF20 for perfectly aligned fibers (orientation tensor = 1,0,0).

Figure 6: Mean Field Homogenization model allows to virtually compute nonlinear behaviors for perfectly aligned fibers which will feed the creation of full field homogenization model in step 2.

(MF = Mean Field)

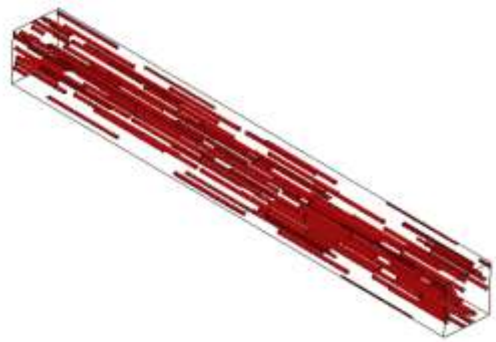


Step 2: Using 0° and 90° virtual data for PPGF20 with a perfectly aligned microstructure, create a full field homogenization model for PPGF20 and refine constituent properties

An RVE is created with 20% mass fraction of straight fibers perfectly oriented along the X axis. The orientation tensor is (1,0,0). It therefore matches the one used to generate the virtual tensile data at 0° and 90° for PPGF20 at the end of step one. The set of virtual tensile data can be used in order to optimize the constituent properties of the material, notably the resin properties and fiber aspect ratio. This refinement is required because of the direct influence of the method used: mean field homogenization models and full field homogenization models don't provide exactly the same behaviors. This is mainly due to the different ways that the microstructure is described in both cases. In mean field homogenization, stress and strains are averaged through the RVE whereas in full field homogenization, they are calculated locally in each point of the RVE constituents.

Figure 7 below is showing the RVE created for PPGF20 with orientation tensor (1,0,0)

Figure 7: Full Field Homogenization model for PPGF20 with orientation tensor (1,0,0)



Boundary conditions and loadings are applied to the RVE FE model created in order to perform a tensile test and get axial and transverse behaviors. The resin properties are then refined in order to perfectly match the virtual data at 0° and 90° for orientation tensor (1,0,0) from step one, as shown on figure 8.

Figure 8: Resin properties are refined to match virtual data at 0° and 90°

(MF = Mean Field – FF = Full Field)

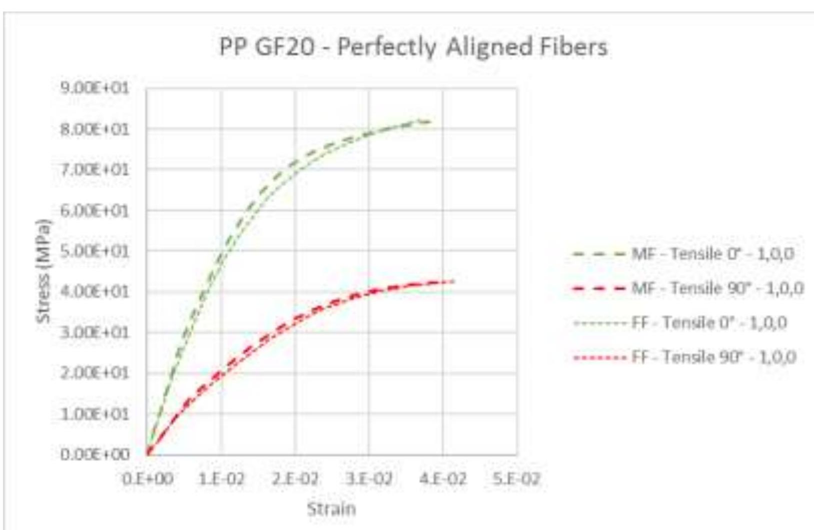


Table 6: Refined resin property (in blue) for full field model PPGF40

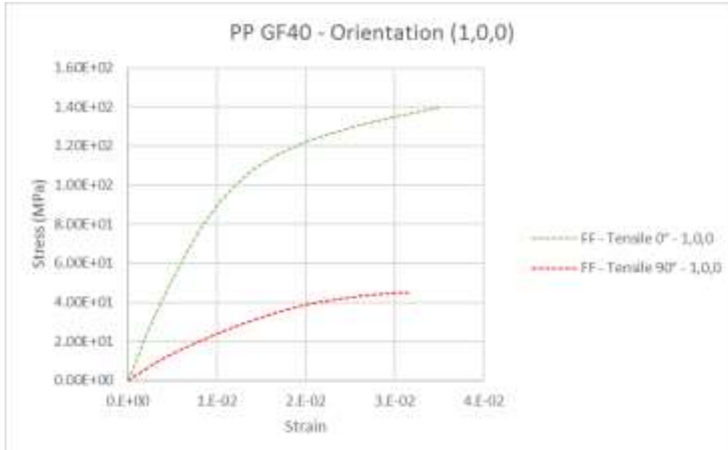
Material parameters	PP Resin	Glass fiber
Density (T/mm3)	9.1e-10	2.54e-09
Young's modulus (MPa)	1900	72000
Poisson's ratio	0.3	0.22
Yield stress (MPa)	10	
Hardening modulus (MPa)	24.7	
Hardening exponent	150	
Hardening modulus 2 (MPa)	25	

Step 3: Create a full field homogenization model for PPGF40 and generate 0° and 90° virtual data for a perfectly aligned microstructure.

An RVE similar to the one created previously for PPGF20 and shown on figure 7 is created for PPGF40. Refined properties identified in step two and shown on table 6 are applied to the FE model and two calculations are performed, one for tensile 0° and one for tensile 90°.

Figure 9 below shows the results obtained for PPGF40 and a perfectly aligned microstructure.

Figure 9: Virtual data for perfectly aligned PPGF40 are generated from the full field model (FF = Full Field)



These two curves are virtual data for 0° and 90° behaviors for a perfectly aligned PPGF40 and will be used as an input to create a mean field homogenization model capable of providing the anisotropic behaviors for every possible fiber orientation tensor.

Step 4: From virtual data generated in step 3, a mean field homogenization model is created for PPGF20 and 0° and 90° virtual data are generated for a coupon microstructure.

At this stage, the situation is similar to step 1 where the mean field homogenization model was built for PPGF20. The only differences here are:

- the input is a virtual input instead of a physical
- The input is for a perfectly aligned microstructure instead of microstructure from real coupon. Consequently, note that this represents 1 less unknown as in our case here, the microstructure becomes known.

Hence, the work here consists of the identification of the correct resin properties in order to match the target behavior provided by the virtual data. Table 7 shows the resin properties identified for PPGF40 from virtual data.

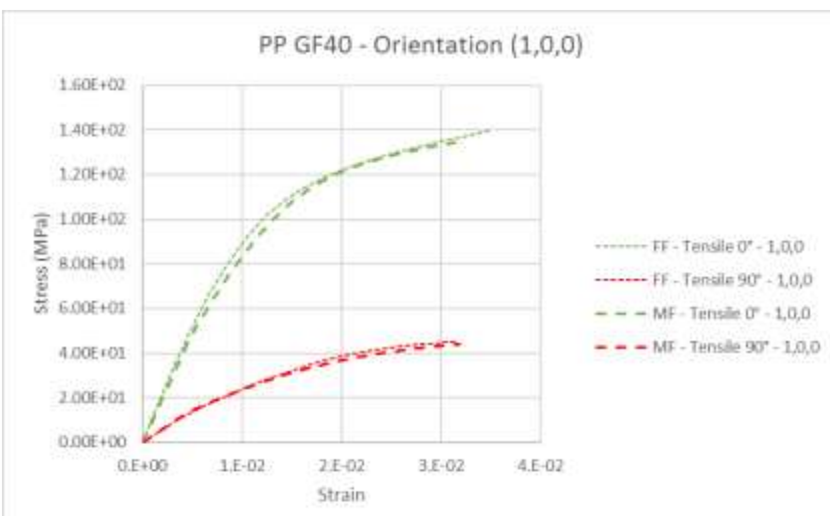
Table 7: Identified resin property (in blue) from virtual data for PPGF40

Material parameters	PP Resin	Glass fiber
Density (T/mm3)	9.1e-10	2.54e-09
Young's modulus (MPa)	2000	72000
Poisson's ratio	0.3	0.22
Yield stress (MPa)	8	
Hardening modulus (MPa)	31	
Hardening exponent	130	
Hardening modulus 2 (MPa)	50	

Figure 10 shows the comparison between 0° and 90° behavior from the full field and mean field homogenization models.

Figure 10: the created mean field homogenization model PPGF40 is capturing perfectly the anisotropic behavior for perfectly aligned fibers provided by virtual data

(MF: mean field – FF: full field)



At this stage, the model is ready to provide anisotropic behavior for every desired fiber orientation tensor. In order to validate the accuracy of this new model, we have to compare its predicted behavior to an existing set of experimental data measured on coupons.

To do so, we have to identify the correct microstructure for PPGF40 coupons cut from plaques. If a microstructure which makes sense for such PPGF40 coupons compared to the one considered for PPGF20 in step one allows us to correctly capture the anisotropic nonlinear stiffness behavior from the experimental data, then, this means that the identified constituent properties are accurate.

Table 8 is showing the microstructure identified which allows to capture measurement data at 0° and 90°:

Table 8: Microstructure identified for coupons PPGF40 cut from plaques

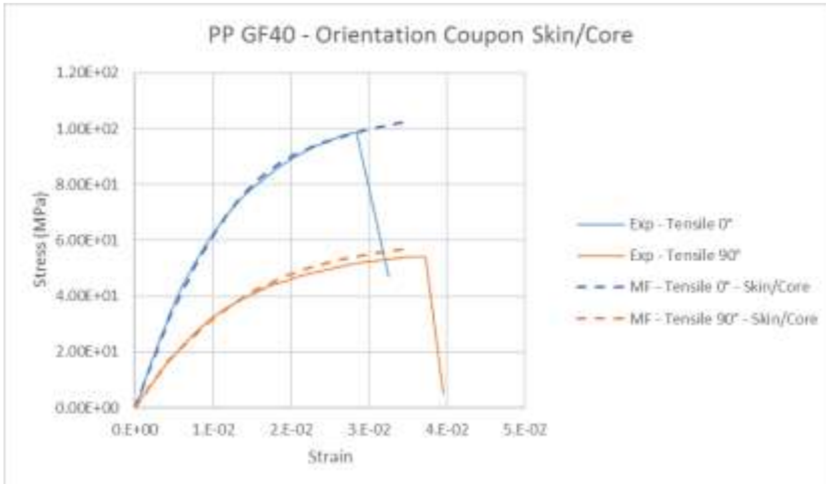
Microstructure parameters	Skin	Core
Proportion of thickness	90%	10%
A11	0.8	0.23
A22	0.18	0.75
A33	0.02	0.02

We can observe that the identified microstructure is more aligned than the PPGF20. This fact makes sense for a material filled with a higher mass fraction of fibers.

Figure 11 below shows the comparison of the anisotropic tensile behavior predicted by the new mean field model for PPGF40 for such a microstructure and a set of experimental data. The model created from virtual data shows very comparable behavior to experiments.

Figure 11: the created mean field homogenization model PPGF40 is capturing perfectly the anisotropic behavior for a Skin/Core microstructure on coupons cut from injected plaque

(MF: mean field)



Summary and Next Steps

In conclusion, the feasibility of a virtual tensile test for a PPGF40 has been proven as being accurate compared to experimental data. A workflow has been proposed to address the virtual prediction of the nonlinear stiffness of a PPGF40, starting from an initial set of tensile test measurements for PPGF20 from the same material supplier. This workflow is a combination of two different multi-scale material modeling techniques: mean-field and full field-homogenization. This demonstration has shown the possibility to save physical test costs in the case where a set of data exists for a given grade and where it is needed to get new data for a similar grade with a different mass fraction of fibers.

In this study, failure has not been addressed. The topic is currently under an optimization process in order to complete this workflow with a proposition fully applicable for the prediction of static but also dynamic behaviors up to failure. The final results of this study will be shown in a webinar on the 19th of October.