# SHEET MOLDED COMPOUND (SMC) TESTING AND UNDERSTANDING FOR A GREATER MODELING

*P. Savoyat*
*e-Xstream engineering, an MSC Software company*
*D. Yu*
*General Motors Corp.*
*R. Harb*
*e-Xstream engineering, an MSC Software company*

## Abstract

Sheet Molded Compound (SMC) materials have been widely used in the industry for more than three decades, bridging the gap in performance between injection molded fiber reinforced plastics and continuous fiber reinforced composites. More recently the industry turned to applying SMCs on structurally more demanding components, targeting among others metal-to-plastic design transfers. Though the material has for long been considered quasi-isotropic with relative success, owing to the manufacturing process, the industry admits today that structural components can't be optimally designed with SMCs based on purely isotropic considerations. Major challenges include more accurate predictions of part response in terms of stiffness, strength and dissipated energy. Hence, understanding and capturing SMC grades specificities and variability are key to developing more accurate numerical simulations, allowing a greater reliance on numerical design iteration in place of costly prototyping.

This paper shares learnings and best practices in terms of SMC material testing, including the effects of coupon geometry and coupon machining locations in compression molded plaques, in order to better understand and describe the material anisotropy. In addition, a modelling methodology for capturing the SMC anisotropic properties due to the underlying microstructure induced by the manufacturing process is also presented.

## General background and work scope

"Compression molding" labeling refers more to a process than to a material nature or a microstructure. Indeed, compression molding can be set up from beam or sheet inputs, and can cover grades from long fiber reinforced plastics (LFRP) to discontinuous chop fibers (DFC) as shown in Figure 1.

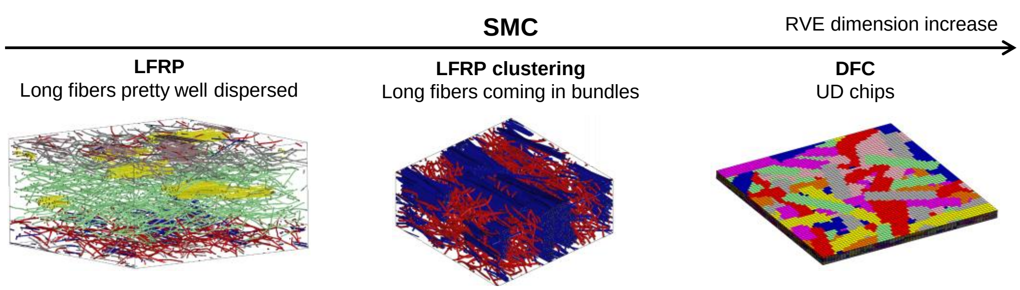


*Figure 1: SMC microstructure from LFRP to DFC.*

This process and associated materials have been widely used over the past twenty years in the industry. Compression molding shows a reasonable takt time with respect to conventional thermoset processes, while the SMC grades themselves bridge the gap from short fiber reinforced plastics (SFRP) to continuous fiber reinforced plastics (CFRP) thanks to much longer inclusions and "intertwined" microstructures. Thus the use of SMC materials is promised to grow in the coming years.

During compression molding process, the material does not flow over long distances (generally less than two third of the longest mold dimension). As a result of this low flow process, the microstructure has so far been assumed in plane quasi-isotropic to ease the modeling of the material response at part level. With increasing simulation capabilities and demand for light weighting, it becomes relevant to search for more accurate modeling capabilities in order to shrink design margin and associated extra-weight.

The work presented in this paper refers to characterization and modeling of a 40%w glass fiber vinyl-ester composite manufactured by compression molding from sheets. Given its microstructure, this grade is much closer to DFC than LFRP and as such, it constitutes a real challenge to model its response both in terms of stiffness and strength.

The aim is to expose learnings and guidelines both for SMC characterization and modeling.

## SMC characterization and understandings

An extensive test campaign has been performed to better understand and capture key phenomenological features of SMCs.

### Plaque manufacturing and test campaign

To identify and separate microstructural key drivers during SMC characterization, plaques have been manufactured based on SFRP experience. Samples have mainly been cut close to the end of the plaque, where both flow and microstructure are more constant, see Figure 2.

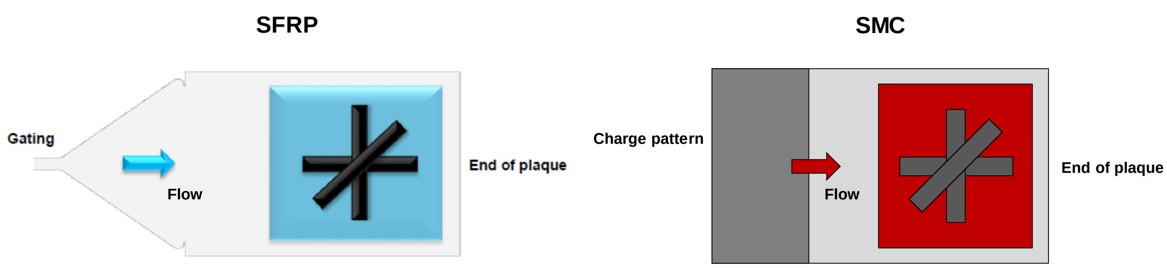


*Figure 2: Similarities with SFRP's plaque manufacturing approach.*

Plaques have been manufactured using several charge patterns in order to capture material anisotropy and weld line among other effects. Figure 3 and Figure 4 illustrate some of the charge patterns manufactured, the resulting plaque and examples of cut plan used.

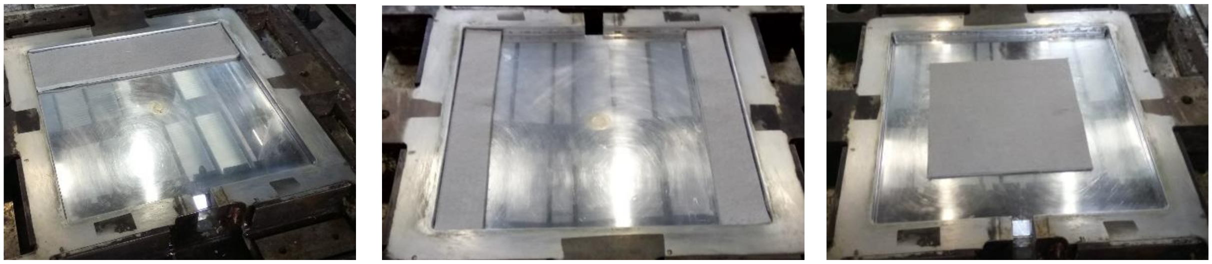

*Figure 3: Charge patterns, similar to SFRP, with weld line and part like.*

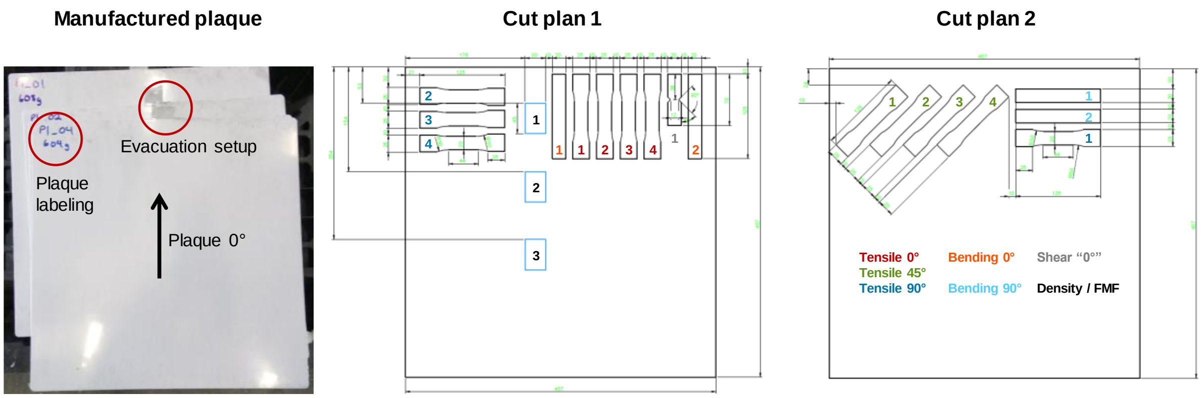


*Figure 4: Resulting plaque and cut plan.*

The test campaign includes:

- Quasi-static and dynamic tensile tests for calibration purpose;
- Quasi-static and dynamic bending tests for validation purpose;
- Inter-laminar shear strength and puncture tests to identify failure under out-of-plane shear and biaxial loads;
- Quasi-static and dynamic tensile and bending tests on coupons showing a weld line in the gauge zone, to characterize the weld line strengths.

## CT scanning: Characterization of the SMC microstructure

To identify the SMC microstructure, micro computerized tomography (CT) scans have been performed.

A first pre-processing phase allowed to identify the ideal resolution to be used in order to analyze a representative sample, as illustrated in Figure 5.

- The smaller the CT scan sample, the finer the CT scan resolution;
- The larger the CT scan sample, the more representative of the material microstructure is the CT scan result.

The optimum identified in this case was a resolution of about 10µm, allowing to have CT scan sample of a similar size to the representative volume element (RVE) while still being fine enough to capture bundle texture and extract orientation tensors (OT).

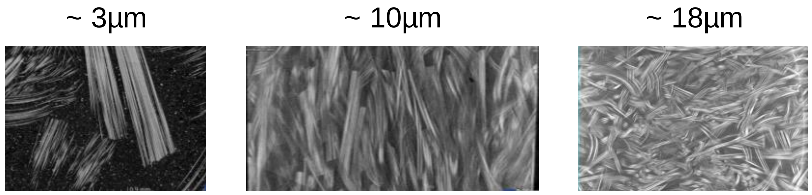


*Figure 5: Resolution and object distinction relationship.*

CT scans show fiber aggregation similar to yarn segments with few fiber separation despite flow. Due to the size of those bundles, the resulting microstructure shows partially curved and even intertwined fiber bundles.

The samples have been extracted along the flow to capture the intensity of alignment with the flow, as illustrated on cut plan 1 in Figure 4. Limited OT variation through the thickness has been observed, and a fiber alignment of about 0.7 in A11 is observed.

The overall alignment intensity, per component and averaged through the thickness, led to unexpected and even counterintuitive results, as shown on Figure 6:

- Almost constant alignment intensity over the first two thirds of the plaque;
- Lower alignment intensity toward end of the plaque (a11 decreasing and a22 increasing with flow).

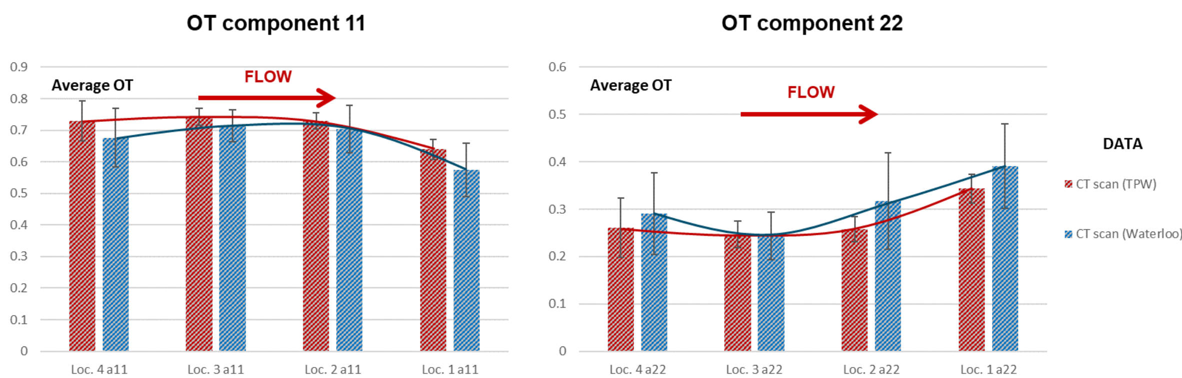


*Figure 6: Overall alignment intensity along flow (average through thickness).*

The weld line has been CT scanned as well, revealing a region of highly perturbed flow. Post-processing of the OT data transversally to the weld line front, see Figure 7, shows a transition domain of about 15mm wide from each side and a very narrow, if existing, neat matrix transition.

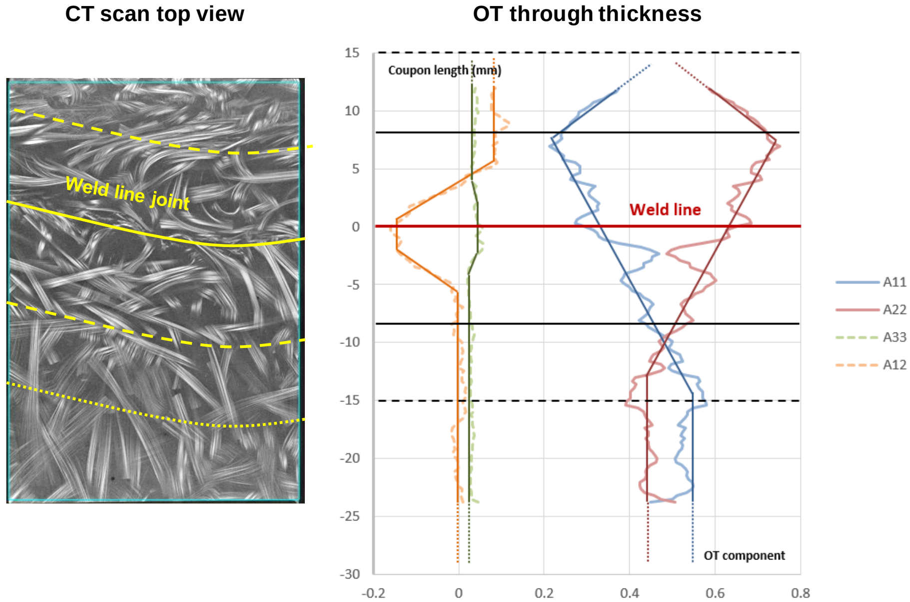


*Figure 7: Weld line width estimation based on perturbed OT.*

## Mechanical testing: Identification of the ideal coupon geometry

To accurately capture the material response, a second pre-processing step has been conducted with several coupon geometries.

In addition to shape selection which takes into account the coupon sensitivity to boundary conditions, the coupon width itself has been identified as playing a significant role with such SMC grade. The fiber inclusion measuring about 25mm long, the RVE is expected to be even larger.

The most challenging phase in coupon design is the gauge aspect ratio, here defined as the ratio of the gauge length to the gauge width. This particular relationship is indeed driving the accuracy of experimental measurements when dealing with large inclusion grades such as SMCs and CFRPs. Figure 8 illustrates two key factors to be considered in the selection of the coupon gauge ratio:

- When large inclusions are present (25mm long here), the load path under tensile 45°, is first driven by a shear load transfer mode. However, the longer the inclusion, the greater becomes the effect of the inclusion tensile load transfer mode from the clamping area through the straight section of the coupon. In case of a short coupon, this load transfer mode leads to an over-estimation of the mechanical properties as the inclusion path artificially stiffens the coupon response (imagine a continuous fiber almost bridging the two clamping areas, the macroscopic stiffness will then be significantly affected by the fiber stiffness).

  Therefore, the longer the gauge length for a given coupon width, the less is artificially over-estimated the coupon stiffness.

- The probability of finding a defect in the area of measurement is the second key driver in coupon design. The bundles operate as weak spots when found around coupon edges. In the case of a long coupon gauge length, the presence of a defect is almost guaranteed, leading to premature failure. The measured strength is not the material strength anymore, but the defect's one.

As a result, the longer the coupon length, the more likely it is that material property is underestimated, as the coupon strength is driven by the presence of a bundle in a "weak" configuration.

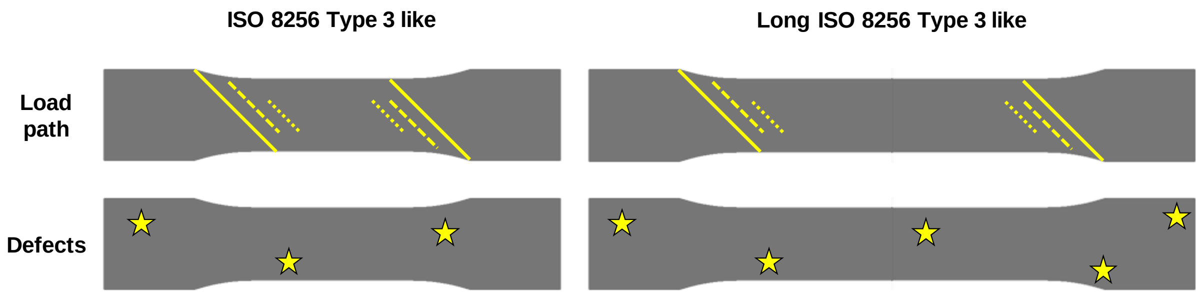


*Figure 8: Gauge length effect on load path and defect likelihood.*

Those two drivers show opposite effects on the recorded properties as illustrated by Figure 9: 1) the coupon stiffness is over-estimated if the gauge length is too short, and 2) the coupon strength is under-estimated if the gauge length is too long. A compromising value was selected to accurately capture the material response, avoiding the over-estimation of stiffness and the under-estimation of strength.

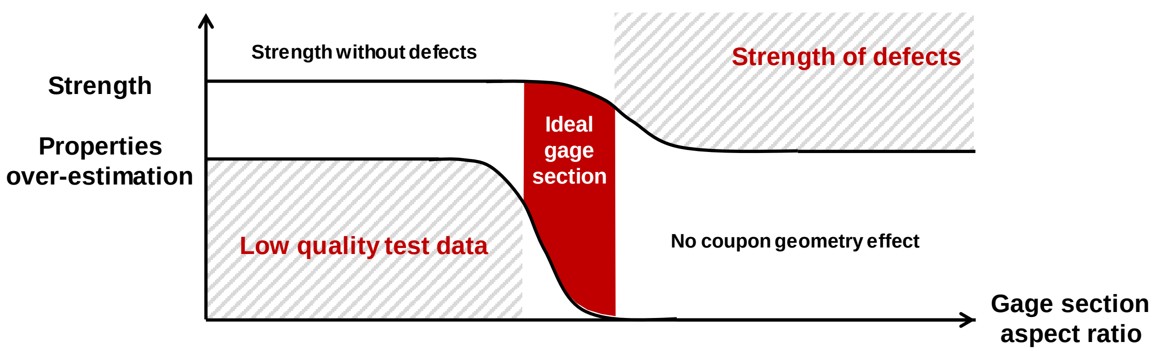


*Figure 9: Ideal gauge section aspect ratio.*

The identification of the coupon geometry and gauge length has been an important this pre-processing to ensure quality test data and deep material insight. In turn, this step will allow to calibrate material cards with relevant inputs.

## Mechanical testing: Characterization of the SMC anisotropy

The anisotropy is related to the ratio between 0° and 90° stiffnesses.

Tensile tests of samples aligned at different angles with flow direction (0°, 45° and 90°) as well as located in different locations (end of the plaque, charge pattern area, from random 2D plaque) indicate significant anisotropy as seen on Figure 10.

- The anisotropy at the end of the plaque is significant with almost a factor of 2 going from 90° to 0° in terms of stiffness. The strength level is significantly affected as well with a factor even higher than 2.

- As observed on CT scans, the alignment intensity towards the end of the plaque is lower than nearby the charge pattern area. The tensile response along the flow as a result is stiffer within the charge pattern area than at end of the plaque.
- It appears that the stiffness difference between a relatively aligned microstructure (end of the plaque) and a random 2D microstructure is very low. This unexpected result demonstrates that the load transfer is significant even with low fiber alignment intensity, suggesting that in this microstructure the underlying long inclusions may highly participate in the load transfer.

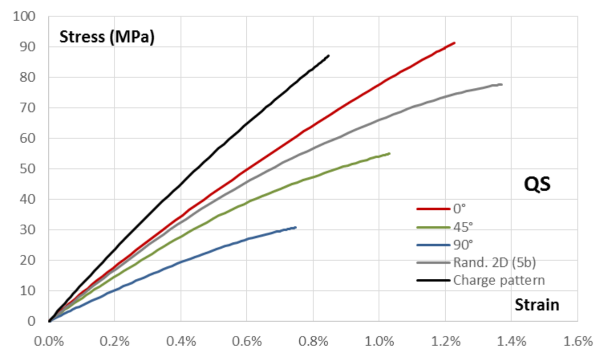


*Figure 10: SMC anisotropy (tensile responses).*

## Mechanical testing: Characterization of the strain rate dependent stiffness

During mechanical testing, an unexpected strain rate dependent trend came out as shown in Figure 11.

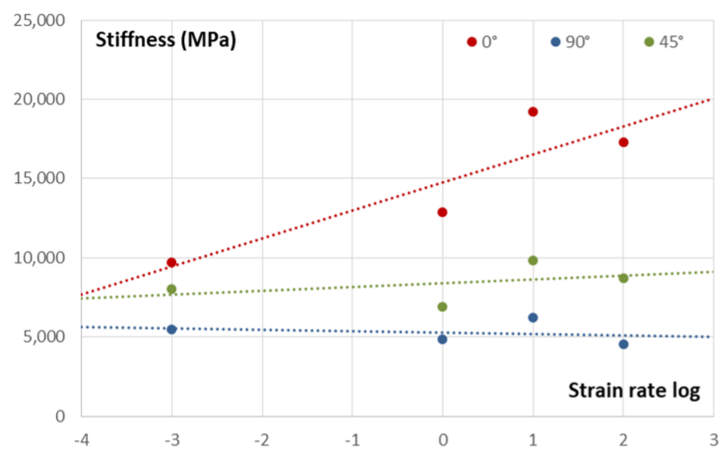


*Figure 11: Stiffness and strength strain rate dependency trends.*

From a general perspective and relative to the static stiffness, reinforced plastics exhibit a greater stiffness sensitivity to strain rate transversally to flow (90°) than along the flow (0°), this because the transverse response dominated by the matrix. In the same time, the stiffness under axial loading (0°) is also expected to increase to a smaller degree (given that this component is more driven by the fiber). As a result, the typical trend is a decrease in anisotropy with an increase in strain rate.

In the current case, the anisotropy significantly increases with strain rate along the flow direction (0°), but remains almost constant transversally to the flow direction (90°). This counter intuitive trend observed on SMC will be further studied carefully in the future.

## Mechanical testing: Characterization of the inter-laminar shear strength

This notion of inter-laminar shear strength is more common with CFRPs. However, given the microstructure observed on CT scans, the inter-laminar shear strength (ILSS) appears relevant to characterize. Besides, SMC parts can be of planar geometry with kinks and therefore be submitted to corner opening-like loads.

The bundles observed in the SMC show a relatively flat cross section and are stacked on top of each other, favoring a potential delamination (shear 13). The inter-laminar strength becomes particularly concerning when a part shows small radius of curvature around corners. The corner opening mainly transfers the load from the inner bundles (inner layers) to the outer bundles (outer layer) thanks to shear 13 due to the Jacobian effect. This failure mode does not exists in SFRP material, where inner skin tension remains the weakest link.

The inter-laminar shear strength test has been performed in a similar fashion to how it is applied on uni-directional (UD) or woven materials via a short beam bend test. It is relevant to notice that in addition to failure profiles, clearly indicating inter-bundle debonding (inter-laminar like), the load displacement curve shape is very similar to UD or woven grades with an almost elastic response cut off at the top, see Figure 12. This failure mode is not predominant at part level but may become limiting in part design when introducing small radius curvatures, and as such should be carefully handled.

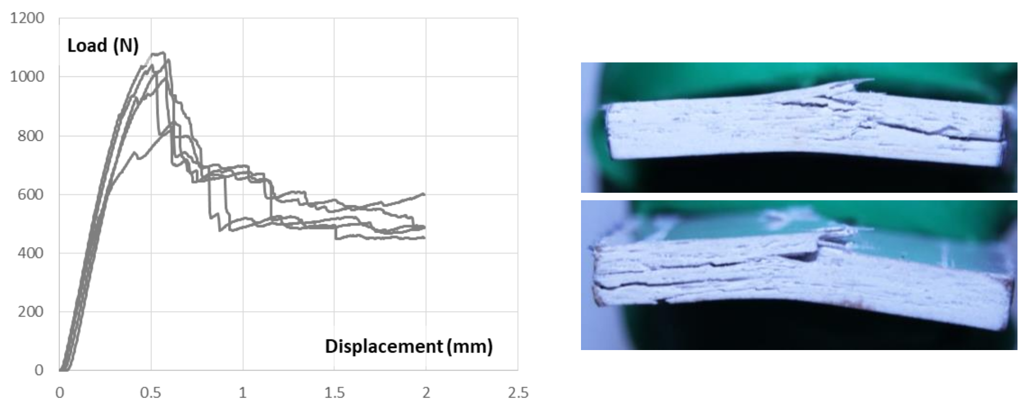


*Figure 12: ILSS test results and failure profiles.*

# Modeling of SMC

Challenges to overcome with SMC modeling are significant:

- Predict OT state over the part thanks to compression molding process simulations
- Capture anisotropy yielded from the microstructure and phase properties
- Capture failure initiation and if necessary damage growth
- Predict response up to elevated strain rates for automotive crash applications

The presented modeling results were obtained with Digimat 2018.1 and Moldex3D R15SP2.

## Process modeling: Orientation tensor prediction

Compression molding simulations have been performed with efforts to capture the alignment intensity as a function of flow.

The default parameters have been used with the improved anisotropic rotary diffusion model to predict SMC OT. It appears that a key driver in SMC modeling is the pressure threshold at mold closure, significantly affecting OT profile and alignment intensity close to end of the plaque.

As shown on Figure 13, the alignment intensity predicted with flow is overall well captured despite the limited drop of a11 and the absence of an increase in a22 close to the plaque end.

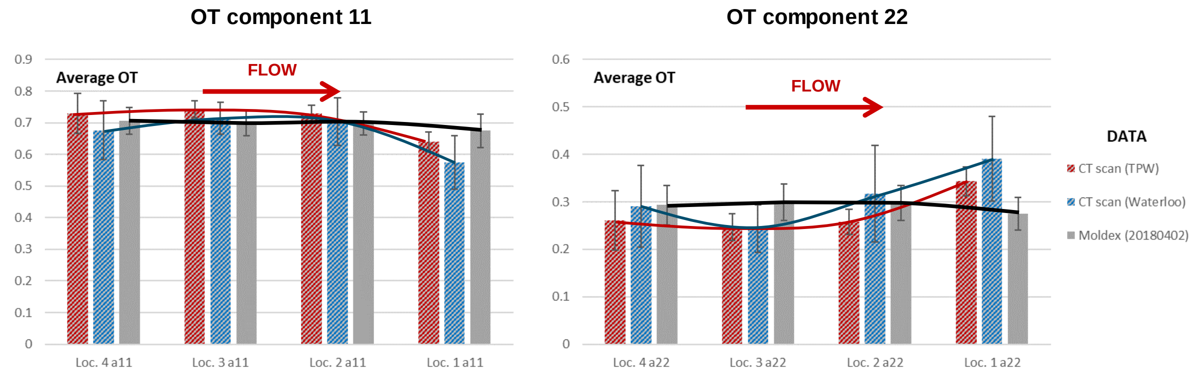


*Figure 13: Alignment trends correlation with process simulation.*

As such it appears that predictions can be used for structural applications with a reasonable level of confidence in the predictions of the fiber orientation data.

## Mechanical modeling: Static stiffness

Thanks to micro-mechanics and mean-field homogenization techniques, the modeling of the SMC anisotropy via the right definition of the constituent behaviors and the fiber orientation characteristics is successful.

An elasto-plastic model has been calibrated based on CT scan OT close to the plaque end. As show on Figure 14, the anisotropy is accurately captured.

- Stiffness prediction relying on another microstructure matches test data (charge pattern area)
- Prediction of bending response matches test data (same material model)

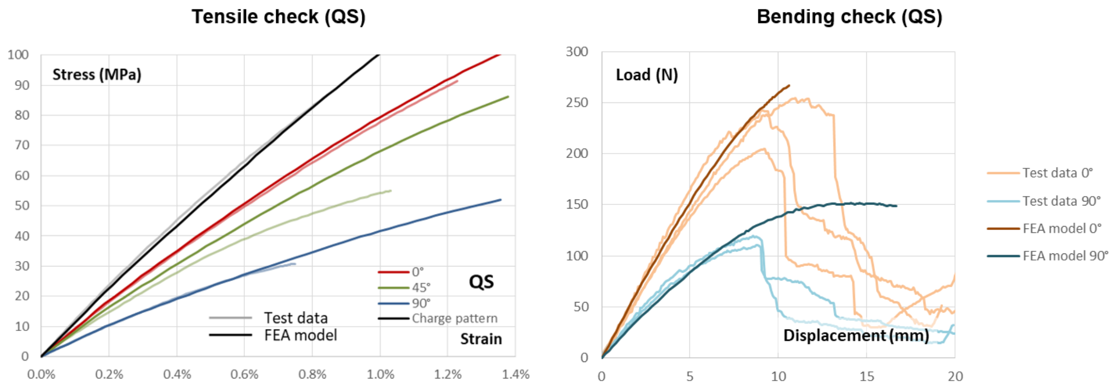


*Figure 14: FEA coupon validation of model under tensile and bending loadings.*

ILSS test simulation shows that stiffness was accurately captured. Plasticity, even if very limited under tensile loading, exhibits a premature saturation, as seen Figure 15.

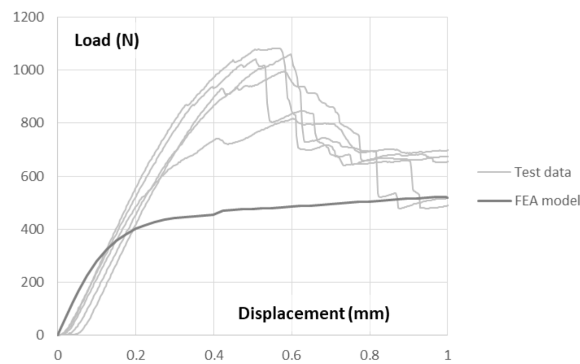


*Figure 15: FEA coupon validation of model under ILSS.*

It appears that the current SMC can be indeed considered almost as purely elastic (still OT dependent) and that the non-linearity is indeed more related to smooth damage growth until final breakage than to plasticity.

## Mechanical modeling: Strain rate dependent stiffness (crash)

As end goal to perform automotive crash simulations, a visco-elastic model has been calibrated and despite limitations shows promising results.

As discussed previously, current mean field solution assumes that the viscous dependency at the composite level is fully handled by the matrix, preventing the possibility of capturing increasing anisotropy with strain rate. Therefore, the Prony series model is calibrated to match the stiffness at elevated strain rates as illustrated in Figure 16.

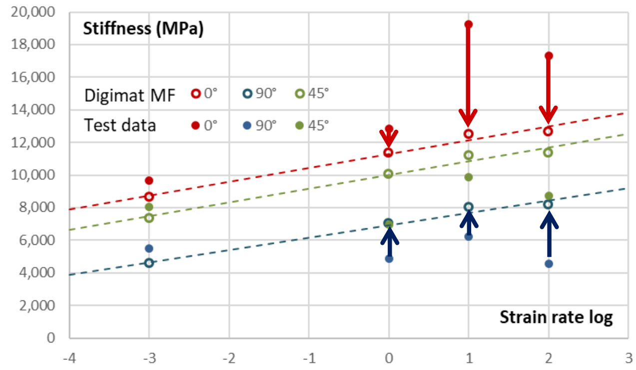


*Figure 16: Visco-elastic model stiffness comparison.*

Despite this inability to capture anisotropy at elevated strain rates, the quasi-static and dynamic bending test simulations show very good agreement to test data in terms of stiffness, as seen on Figure 17.

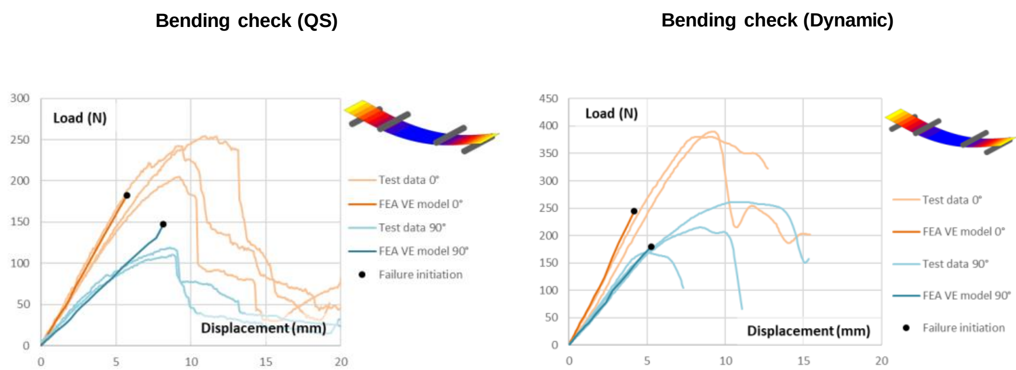


*Figure 17: FEA coupon validation of model under bending tests.*

## Mechanical modeling: Towards failure

As discussed previously, SMC microstructure makes failure prediction and damage propagation modeling a real challenge:

- Large inclusions aggregates (fiber bundles);
- Almost purely elastic response;
- Non-linearity driven by smooth damage growth.

The software sets up mean field pseudo grain technology to predict failure using indicators such as Tsai Hill 3D transversally isotropic. When looking at biaxial load case with puncture test, it appears that such criteria is very conservative, see Figure 18.

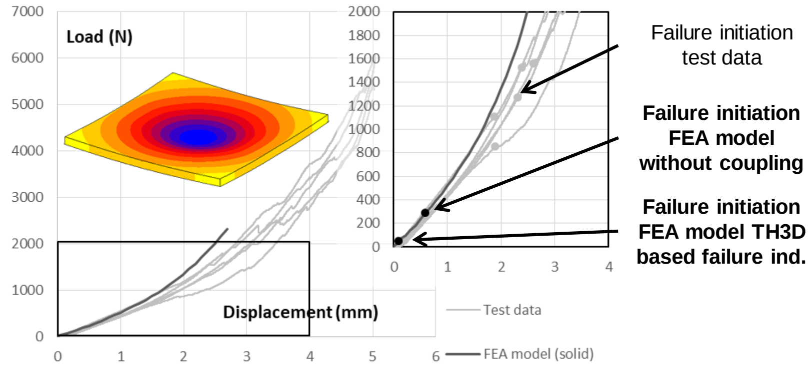


*Figure 18: FEA coupon validation of model under puncture test.*

As a results of our previous observations, the most efficient solution with the current modeling capabilities is the definition:

- an elastic/visco-elastic model, and
- an "uncoupled" macroscopic failure indicator (only sensitive to main local axis of fiber alignment, not to the intensity in alignment itself)

With such definition the material non-linearity is captured through a smooth damage growth (isotropic stiffness reduction).

The use of such modeling approach, see Figure 19, already offer a relevant solution for structural applications and will be validated at the structural level.

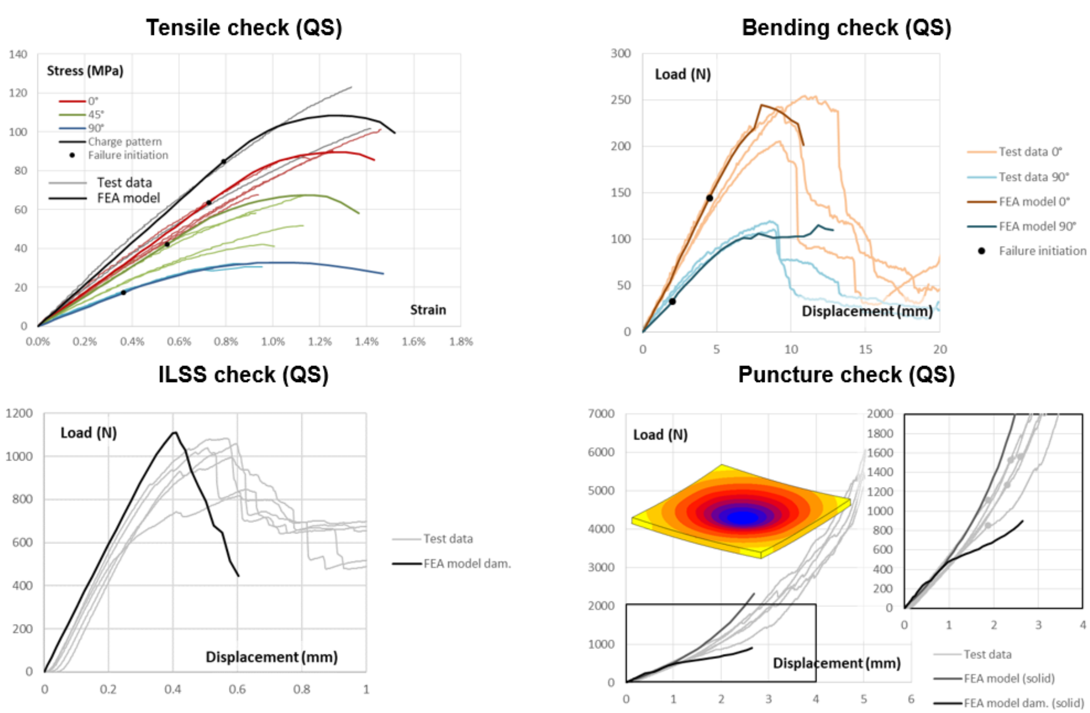


*Figure 19: Overview of model coupon FEA validation.*

To better support customers and overcome such limitation regarding biaxial loads, Digimat now provides a matrix accumulated plastic strain failure criteria. This criteria consist in an acceptable plasticity level in the matrix for a given triaxiality. By construction, this failure criterion allows to postpone failure during calibration for biaxial loading compared to tensile failure. The modification of such failure indicator to support elastic and visco-elastic models (not showing any plasticity) should open the door to more accurate prediction of failure initiation.

## Summary and Next Steps

Interesting learnings came out of the glass fiber vinyl-ester SMC test campaign performed:

- Microstructure with fiber bundles and unexpected alignment intensity trend with flow
- Significant anisotropy with stiff response even in random 2D microstructure
- Counter intuitive stiffness strain rate sensitivity at elevated strain rates
- Bridging microstructure to continuous fiber reinforced plastic with identification of inter-laminar shear strength (not existing with short fiber reinforced plastics)
- Identification of suitable coupon geometry to characterize such grade

According to the performed work, SMC modeling status is as follow:

- Process simulation is already useful to predict orientation tensor
- Mean field technology successfully captures anisotropy and bending responses
- Stiffness strain rate sensitivity is captured with limitations on anisotropy at elevated strain rate, and remains promising for further structural applications
- Failure of SMC material, showing microstructure close to discontinuous fiber chips, remains challenging and even if current failure package already provides a relevant solution despites some limitations, further improvements already are identified

Further work will consist in:

- Validating at structural level the calibrated models and set up workflow
- Enhancing orientation tensor prediction for compression molding process
- Investigating modeling of strain rate dependent stiffness
- Improving failure and damage propagation predictions
- Studying carbon fiber SMC for higher performances

## Acknowledgements

Results were achieved thanks to efforts of Eva María Acuña Fulgencio and Aitor Arriaga from Leartiker, Kleinteich Thomas from TPW, Srikar Vallury and Anthony yang from Moldex3D, Pete Foss and Alwin Xu from GM and Thierry Malo, Maxime Melchior and Sylvain Calmels from e-Xstream.