STRUCTURAL VALIDATION OF MATERIAL MODEL AND CAE METHOD ACCOUNTING FOR SHEET MOLDING COMPOUND (SMC) PROCESS

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Abstract

Sheet Molding Compound (SMC) materials have been widely used in industry for many 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 more structurally demanding components, targeting among others metal-to-plastic conversions. Although the material has for long been considered planar isotropic with relatively good 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. This will allow a greater reliance on numerical design iterations in place of costly prototyping.

This paper comes as the second part of work presented in 2018, where characterization learnings and modeling at the coupon level were presented. It aims at providing an overview of typical workflow which can be followed to model SMC part structural performance while accounting for the manufacturing process, from compression molding process simulation up to crash simulation.

General background and work scope

“Sheet molding compound” or “Compression molding” labels refer more to a process than to a material nature or microstructure. Indeed, compression molding can be set up from extruded or sheet inputs, and can cover grades from long fiber reinforced plastics (LFRP) to discontinuous chop fibers (DFC) as shown in Figure 1.

![SMC family](image)

*Figure 1: SMC material family, 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 expected to grow in the coming years [1].

During the compression molding process, the material does not flow over long distances (generally less than two thirds of the longest mold dimension). As a result of this moderate flow process, the microstructure has so far been assumed in plane quasi-isotropic to ease the modeling of the material response at the part level. Typically, plaques are molded with approximately 50% charge coverage to obtain mechanical test specimens. 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.

Previous work presented learnings and guidelines both for SMC 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 [2].

The work presented herein corresponds to the structural validation of the CAE method and associated material model.

**Experimental methods**

**Materials and geometries**

The material used was a 40 %w glass fiber vinyl-ester composite manufactured by compression molding from sheets, Van Wert GHS SDS17 855 from Continental Structural Plastics. Manufactured part consists of an inner seat panel. Compression molding was performed at Fraunhofer Project Center in London, ON, using a Dieffenbacher DCP-U 2500/2200 press. A decreasing mold speed closure profile and a consolidation pressure of 100 bar were used. The mold temperature was set to 150 °C and curing lasted 180 seconds.

9 charge patterns were used in order to study different microstructure at structural level, including the presence of intentional weld lines. Figure 2 illustrates three of the most studied charge patterns with a central charge targeting typical industry practice with radial material flow, two charges meeting at part mid length to evaluate weld line weakness from a structural perspective and an off-centered charge inducing more significant flow resulting in material anisotropy.

![Figure 2: Representation of three charge patterns prior mold closure and flow, central charge (left), off-centered charge (center) and two charges (right).](image-url)
Testing

Computerized tomography (CT) scan were performed at Waterloo University in order to measure fiber orientation tensor to assess process simulation results. To do so, samples of 50 x 10 mm were cut at different locations with the full part thickness, allowing to perform CT scans of 10 x 10 mm with a resolution of 5 µm.

Mechanical tests consisted of bending and punch tests at part mid-length, on the convex side under the impactor as presented in Figure 3. Both bending and punch impactor radius are 60 mm. In those two configurations, different charge patterns were tested under quasi static and dynamic load cases, respectively 0.01 m/sec and 2 m/sec. Impactor load and displacement vs. time is the resulting output of those tests. Typical response is displayed in Figure 4.

![Test setup in bending configuration](image)

*Figure 3: Test setup in bending configuration*

![Resulting load-displacement curves in quasi-static load case, in bending (left) and in punch (right) configurations.](image)

*Figure 4: Resulting load-displacement curves in quasi-static load case, in bending (left) and in punch (right) configurations.*
Numerical methods

To model SMC parts at a structural level, a similar approach to what is common for Short Fiber Reinforced Plastics (SFRP) can be followed: I) the manufacturing process simulation in Moldex3D R16 predicts the material local microstructure description as orientation tensors and the position of the potential weld lines, II) mapping of the orientation tensors and weld line positions, to the structural mesh with Digimat-MAP 2018.1 III) material modeling of SMC capturing anisotropy thanks to orientation tensors, and the weakness of weld lines at structural level with Digimat and IV) the structural FEA simulation performed with LS-Dyna 9.1 coupled to Digimat-CAE 2018.1. Similar to short fiber materials, we expect to benefit from accurate SMC material modeling, in terms of stiffness and failure, as illustrated by Figure 5.

I. Compression molding simulation
Moldex3D simulation in two steps
Draped charge

II. Mapping of microstructure information
Orientation tensor and weld line mapping from process simulation to structural mesh
Orientation tensor field

III. Material modeling
Digimat material card
Stress field curves for various loading angle

IV. Structural simulation
LS-Dyna simulation coupled to Digimat
Damage field at load drop

Figure 5: SMC material modeling workflow at structural level, I) process simulation, II) mapping of microstructural information, III) material modeling and IV) finite element analysis.

Manufacturing process simulation

Compression molding can simulated using Moldex3D in two steps: I) a draping analysis and II) a compression molding analysis as illustrated by Error! Reference source not found.. The draping analysis can be simulated with LS-Dyna and consists of a gravity sag load case, followed by mold closing. In this first step, the charge transitions from a flat geometry to lie in the mold cavity as “draped” solid charge in contact with both mold halves. The second step as the mold closes is clearly in the fluid dynamic domain and is well handled by the Moldex3D solver with a viscous material model. The draped charge will as a result flow to fill the mold cavity, orienting the SMC material. As a result of these two steps, orientation tensors can be retrieved and potential weld lines identified.
Figure 6: SMC manufacturing process simulation workflow, I) draping of initial charge (left) and II) compression molding (flow phase) of draped charge (center).

The Moldex3D material model used for process simulation corresponds to the one characterized and calibrated during previous work. Initial charge thicknesses were adjusted to reach consistency with resulting part thickness and weight. Three different compression molding simulations were run to predict microstructures corresponding to charge patterns presented in Figure 2.

Mapping of process results

Digimat-MAP is a useful tool to map information from one mesh to another. In this case, the interest is to map information coming from the manufacturing simulation of Moldex3D to the structural mesh of LS-Dyna. It is now possible to map orientation tensor, fiber content, fiber length and weld line fields resulting from a compression molding simulation to both solid and shell structural meshes.

Material modeling

Digimat can model SMC material capturing key characteristics: I) anisotropy, II) failure and damage as well as III) weld line weakness. Digimat-MF allows the creation and calibration of material cards, while Digimat-RP enables to efficiently couple Digimat material cards to standard finite element analysis software such as LS-Dyna, as discussed later.

Characterization has shown that SMC materials consist of fiber bundles with various orientations. With such microstructure, SMC materials are far from mean field theory assumptions, that consider an inclusion such as a fiber in a homogeneous medium. As an alternative solution showing good success, the inclusion is fiber bundle. Assuming a perfect fiber alignment of fiber in a bundle, inclusions are transversally isotropic and based on unidirectional homogenization.

As mentioned in previous work, a pragmatic modeling approach is to rely on an uncoupled macroscopic failure indicator, labelled multi-component in Digimat. As a consequence, failure initiation is sensitive to only the main local axis of fiber alignment and not to the intensity in alignment itself. Based on this failure initiation, Digimat then provides a powerful progressive damage model illustrated by Figure 7. This feature replicates observed trends during testing: smooth damage growth at a macroscopic level due to multiple damage initiations up to a catastrophic coalescence state. It comes as an isotropic damage growing from failure initiation, linearly or following a power function, over an equivalent strain domain. This damage model can be used with an element deletion trigger once damage equivalent strain domain is consumed.
The weld line weakness comes from the absence of bridging bundle through the weld line. As a result, the strength of the weld line is not driven by the inclusions but by the matrix. With that in mind, the weld line strength of a carbon fiber SMC material should not be much different from the one of a glass fiber SMC material. The stiffness is not significantly affected since the neat matrix domain which can be identified is very thin and negligible compared to the element size. In this early work, the weakness of weld line had to be handled thanks to a strength knock down factor compared to the pristine material. A dedicated material model, with the same stiffness but downgraded strength, was then assigned to weld line elements sets.

The Digimat material model used for mechanical simulation corresponds to the one calibrated during previous work. The damage model has been updated in agreement with macroscopic observations with a larger equivalent strain at break: a consequence of mesh size discrepancy between calibration and structural meshes used previously in the material model calibration from plaque data.

**Structural simulation**

The experimental test setup part clamping was simplified to fixed displacement nodes as illustrated by Figure 8. The impactors were modeled as a surface body with constant speed. Simulations were performed using LS-Dyna explicit for both static and dynamic load cases. A solid mesh of type 7 elements were used having a size of 3 mm and 3 elements through the thickness. Part thickness was updated per regions based on part measurements. Reasonable mass scaling were used. Digimat was coupled as user-subroutine to provide local material response during the simulation, accounting for mapped information from process simulation for each element and appropriate failure indicator in presence of weld lines.

![Figure 8: I) Complete test setup design (left) and LS-Dyna model of the test setup in bending (center) and punch (right) configurations.](image-url)
Results and Discussion

Process simulation assessment

It has been observed in previous work that SMC materials do not exhibit a significant skin-core effect contrary to SFRP. As such an average orientation tensor over the thickness is an objective indicator, easing the orientation tensor comparison of process simulation and CT scan measurements. Figure 9 presents the comparison of central charge pattern orientation tensors between CT-scan measurements and process simulation predictions.

![Figure 9: Orientation tensor comparison with first and second orientation tensor component comparisons between CT-scan measurement and process simulation results (left), for various location of central charge pattern part (right).](image)

The orientation tensor comparison for the central charge pattern shows a reasonable agreement overall. Anisotropy is moderate at location 1, as expected given it is the center of the plaque where least flow is expected. Higher anisotropy due to larger flow at location 2 is captured. One can notice that wall domains at locations 3 and 6 show a less accurate but reasonable fit.

Resulting orientation tensor predictions of the three charge patterns studied are presented in Figure 10, with the warmer the vector color, the higher the local fiber bundle alignment.

![Figure 10: Process simulation orientation tensor predictions, central charge (left), two charges (center) and off-centered charge (right).](image)

When putting in perspective the variation of anisotropy that parts will show, the process simulation results seem acceptable to perform structural simulations of SMC structures.
Mechanical simulation assessment

Bending configuration

Bending configuration is representative of numerous load cases at structural level. Indeed, the geometry of the inner seat in bending configuration leads to profile opening, which generates significant out of plane shear stress in the corners of the part and significant skin tensile stress opposite of the impactor. This failure mode is observed from macroscopic perspective with limited to moderate stiffness loss prior a significant load drop as shown in Figure 4.1. As a result the part breaks into two domains, even though, due to material toughness the inner seat keeps carrying load via the edge flanges even with a major crack at mid length. A comparison of test results with simulations is provided for each charge pattern for both static and dynamic load case in Figure 11. Two simulations using different material cards are compared for each load case: first the Digimat material card as documented in this document, relying on Moldex3D orientation tensor and weld line, using damage with progressive failure and element deletion; second an LS-Dyna material card Mat24 capturing an averaged response of the SMC material, relying on an isotropic elasto-visco-plastic behavior and element deletion.

![Comparison of quasi-static (first row) and dynamic (second row) loading bending configuration results for central charge (left), off-centered charge (center) and two charges (right), with test data (grey), Digimat material card (blue) and LS-Dyna material card (light grey).](image)

First outcome of this comparison is similar for each load case: the Digimat material model correlates well with test results overall. Part stiffness is well captured in all load cases but is not key to differentiate from LS-Dyna material card, even though the LS-Dyna card provides slightly over predicted stiffness. The inner seat part and/or bending load case configuration may not be the most relevant to highlight the benefit of anisotropic material card, varying with reinforcement alignment intensity over the part. Indeed, Digimat material card enlarges the gap with LS-Dyna material card when getting closer to peak load. Damage initiates and propagates in the first failure...
mode scenario with much better agreement with test data using Digimat material card enabling to capture peak load and displacement at load drop with good accuracy. Space for improvement remains on the damage propagation side in order to better capture the energy dissipation after load drop. In overall, damage propagation appears to be too much significant after catastrophic failure leading to under estimation of dissipated energy.

One may notice that the failure scenario even captures small signals through kinematics as shown in Figure 12. With very low mass scaling allowing maximum representativity of FEA simulation, in addition of stiffness and II) catastrophic failure, Digimat prediction captures I) minor events such as multiple crack initiations slightly reducing overall part stiffness, as well as III) second major even highlighting that failure kinematic is consistent with experiments. Those results are very satisfying and encouraging to implement the presented workflow in an industrial context knowing that there still is space for improvement on the damage management side.

**Figure 12**: Analysis of central charge pattern part failure scenario in bending configuration, comparison between test results and Digimat prediction.

**Punch configuration**

Punch configuration is interesting as a validation test for automotive industry because it represents the local impact load case family, covering especially head and pedestrian impact tests. In this scenario, even though part overall stiffness does not appear to be sensitive to charge pattern, see Figure 4, the failure profiles are way different as shown by Figure 13.

**Figure 13**: Inner seat failure profile in punch configuration per charge pattern highlighting crack path.
The off-centered charge pattern, generating higher alignment intensity along the part long dimension, prevent cracks to propagate along part width unlike central charge pattern, showing a lower alignment intensity. Load drop occurring at the same load for those two configurations seems to indicate that in both cases, the catastrophic crack initiates below impactor, on the opposite part face. However, it suggests as well that crack propagation observed on central charge is contained to a domain similar to impactor cross section thanks to higher reinforcement alignment, leading only to a “go through” profile. Once the catastrophic crack propagation occurs on a centered charge pattern part, the load is then transferred through the part edges similarly to observed failure scenario in bending configuration. In case of two charge pattern, failure profile is neat and following weld line path along part width due to weakness related to absence of bridging fibers.

Macroscopic outputs of those tests in terms of load-displacement curves are provided through Figure 14, including comparison of simulations using Digimat and LS-Dyna material models. Similarly to the bending configuration, the Digimat material model provides much better fit in stiffness, peak load and as a result in terms of displacement at load drop. Similarly to bending configuration as well, damage propagation may be over-estimated after peak load, leading to an under-estimated energy dissipation.

![Graphs showing load-displacement curves for central charge, off-centered charge, and two charges configurations](image)

*Figure 14: Comparison of quasi-static (first row) and dynamic (second row) loading punch configuration results for central charge (left), off-centered charge (center) and two charges (right), with test data (grey), Digimat material card (blue) and LS-Dyna material card (light grey).*

On the other hand, in this punch configuration some cases show a premature failure up 25% in load. This suggests failure occur prematurely and that damage propagates faster in simulation than in reality. Indeed, both observations were already made during calibration phase on plaques as illustrated in Figure 15. During a coupon level puncture test, failure occurs earlier than in reality and damage propagates faster. This leaves room for improvement mentioned previously to enhance failure and damage with Digimat material card. The very encouraging aspect remains...
that Digimat is on the safe (conservative) side and allows safe design already lightening design with more accurate predictions.

![Figure 15: Compromise reached during Digimat material card calibration on puncture test.](image)

**Qualitative assessment**

Simulations show as well very good qualitative indications of secondary failure modes: where damage initiates without leading to structural failure. Figure 16 illustrates the comparison of central charge pattern part damage after bending load case with great consistency. Such indication appears to be very valuable in early design phase when structural failure scenarios may change for a secondary failure mode.

![Figure 16: Qualitative assessment of secondary structural failure modes between real and virtual parts.](image)
Summary and Next Steps

A significant sheet molding compound (SMC) structural validation campaign has been performed involving process and mechanical simulation assessments. Key outcomes are:

- A two phase draping compression molding process simulation already provides reasonably good orientation tensor predictions for SMC materials.
- Mean field theory successfully captures anisotropy of SMC materials thanks to fiber bundle inclusions, even if the tested component and load case may not be the most appropriate to highlight this benefit.
- Weld line weakness is accurately captured with the presented workflow, increasing confidence to design parts with several charge patterns and inserts.
- The applied workflow captures peak load and displacement at peak load with great success in addition to highlighting potential secondary weak spots which could compete for structural failure. Space for improvement remains to capture 1) damage propagation in order to refine load drop in punch configuration and 2) energy release after catastrophic event to design more precisely energy absorbing parts.
- The developed workflow is ready for industrial validation and implementation.

Further work will consist in:

- Improving failure and damage propagation predictions.
- Studying carbon fiber SMC for higher performances.
- Implementing the SMC workflow to automotive production development and CAE process.

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References

2. Pierre Savoyat and David Yu. Sheet Molded Compound (SMC) testing and understanding for a greater modeling. SPE ACCE. 2018