A Simulation Approach to Combine Multi-Scale Model Features with Failure at Composites Level for Short Fiber Reinforced Polymer

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Abstract: *In order to facilitate the application of thermoplastic composites in the automotive industry for weight saving and fuel economy, an advanced simulation approach is applied to evaluate the performance of an injection molded short fiber reinforced composites beam.*

A fully coupled Digimat® with Abaqus homogenization method for multi-scale modeling is explored and compared to an uncoupled Digimat® with Abaqus approach which uses an Abaqus User subroutine. A failure model is calibrated to predict short fiber reinforced composites failure. The results obtained with this model are presented, demonstrating accurate prediction results. The developed model with homogenization features is able to distinguish the behavior of beam with different injection molded process and is validated by comparing predicted results with experimental data of beam flexure test under different boundary conditions.

Keywords: *Composites, Polymer, Injection Molded, Short Fiber, Multi-scale Modeling, Homogenization, Failure.*

1. Introduction

Improving fuel efficiency and reducing carbon emission are the automotive industry megatrends which can be addressed by replacing traditional heavier metal auto part with the light weight polymer composites. Polymer composites also offer design flexibility, easy fabrication and parts consolidation. Accurate material models with capability to predict the polymer composites behavior including damage progression and failure are necessary to reduce experimental testing cost and to estimate the performance of part designs with stringent safety requirements. DuPont offers the polymer composites solution by not only developing its Vizilon™ thermoplastic composites (TPC) material models, but by also improving the composite material models in various CAE softwares. A new constitutive model for continuous woven fiber reinforced TPC has been developed (Volgers, 2015). This work aims at modeling short glass fiber reinforced PA-66 nylon with micromechanics features and appropriate failure criteria.

As composite properties depend on the material microstructure, including fiber amount and orientation, they are adequately modeled from micromechanics, in particular with mean-field homogenization techniques. Digimat®, a software provided by e-Xstream Engineering an MSC software company (Digimat-MF, Section IV.2), has implemented the mean-field homogenization method to represent the original heterogeneous material by an equivalent homogeneous one as shown in Fig. 1. This software is selected to model the short fiber reinforced composites and largely improves the stiffness prediction compared to the traditional phenomenal orthotropic modeling method. However, there are limitations in its current failure models for short fiber composites. Therefore, an uncoupled Digimat® with Abaqus model is developed using in-house scripts and Abaqus User subroutine to convert the Digimat® material parameters into an Abaqus anisotropic elastic plastic model. Thereafter, Abaqus failure criteria are added to the uncoupled Digimat® with Abaqus homogenization model, which is calibrated by experimental tests. The model is then validated by comparing the predicted results with test data of dogbone samples and generic DuPont beams made using different injection molding processes and tested under different boundary conditions.

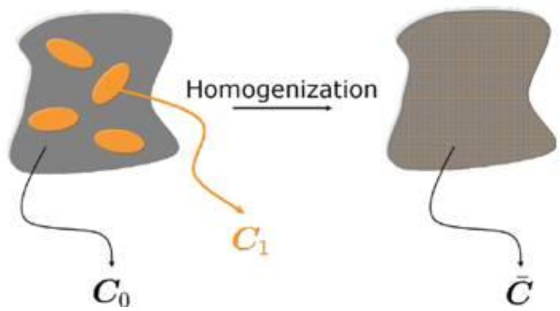


Figure 1. Heterogeneous material (left) from which its equivalent stiffness $\bar{C}$ (right) is computed from mean-field homogenization.

2. Experimental Test

2.1 Dogbone Tension Test

Short fiber reinforced composite plaques are manufactured by injection molding a thermoplastic polymer compounded with short glass fiber into a 125 mm x 125mm x 3mm plaque. Dogbone shaped coupons are cut from the plaque at three different angles, 0°, 45°, and 90°, with respect to the primary flow direction as shown in Fig 2. These samples are then conditioned to achieve equilibrium moisture content at 23°C and 50% RH. Quasi-static tension tests are conducted on the samples to measure the force and displacement. The processed stress-strain curves for three angles are summarized in Fig 3. The material behavior is anisotropic. The 0° tension behavior is stiffer than the other two angles because the short fiber orientation is more aligned in the flow of 0° direction. The failure strain at 45° is much higher than that observed for the other two angles.

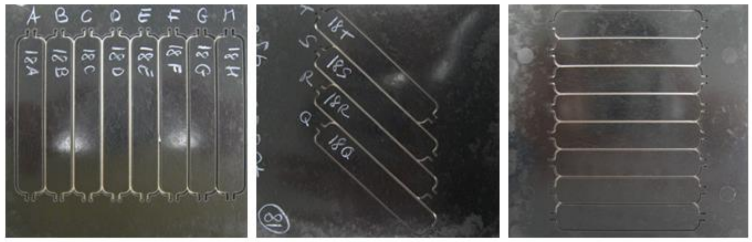


Figure 2. Samples at coupon level are cut from injection molded plaque at 0°, 45°, and 90°

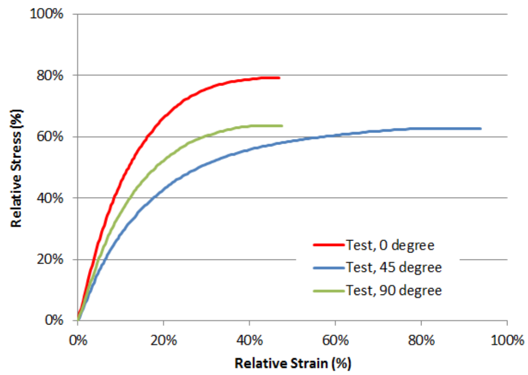


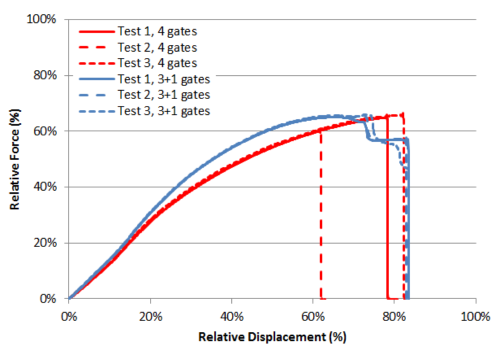
Figure 3. Dogbone quasi-static tension stress-strain curves at three angles.

2.2 Structural Beam Flexure Test

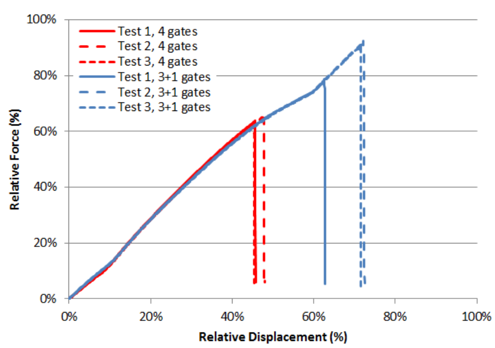
Structural beams with the geometry of 730mm in length and 140mm in width are manufactured by two different injection molding processes. In the first case, referred as 4 gates injection, all four injection ports along the length of the beam are opened at the same time. The injection flow meets at the middle of the beam forming a weld line at the middle. The second case, referred as 3+1 gates injection, has injection starting simultaneously at 3 ports earlier than the last port, generating a weld line away from the middle of the beam. All injected beams are conditioned to reach the equilibrium moisture content at 23°C and 50% RH.

The beams are mounted on a test bed with customized fixture for 3 point flexure tests as shown in Fig 4. Two different boundary conditions are tested: no constraints at the ends which is called free boundary, and clamped by bolts at both ends which is called clamped boundary. Three repeat tests are conducted for each injection molding process beam with each boundary condition. The loading nose is driven by hydraulic machine with constant speed control. The force and the displacement of the loading nose are measured and the video and failure picture are recorded for each test. Fig 5 summarizes the measured force-displacement curves for different injection processes and boundary conditions. The 3+1 gates injection beam has a stiffer response than 4 gates injection beam with free boundary condition. In the clamped boundary case, 3+1 gates injection beam stiffness is very similar to 4 gates injection beam, however, 3+1 beam dissipates more energy due to the higher failure load than 4 gates injection beam. These observations are used to estimate the model capability in the following sections.

Figure 4. Structural beam flexure test set up.



(a) Free boundary



(b) Clamped boundary

Figure 5. Force-displacement curves of beam flexure tests

3. Phenomenal Orthotropic Modeling Method

The phenomenal orthotropic model defines the material properties at the composites level and excludes the microstructure effect. In order to directly extract the composite property parameters from the dogbone tension test data, the phenomenal model assumes that the fibers are perfect aligned in the molding flow direction and neglects the fiber orientation change through the sample thickness. Orthotropic elastic stiffness is obtained by fitting the initial linear part of the stress-strain curve. The yield stress versus plastic strain data points based on 0° curve is used to define the reference plastic curve. A set of Hill's yield ratios are applied to define the orthotropic yielding (Abaqus Section 23.2).

The developed orthotropic model is used to simulate the dogbone tension tests and the predicted results agree well with test data as shown in Fig 6. A mold filling analysis using Moldflow® is conducted on the structural beam to estimate the fiber orientation for two different injection molding processes. The same orthotropic model combined with the orientation distribution is employed to simulate the beam flexure tests and the comparison between model results and test data are shown in Fig 7. The model over-predicts the beam stiffness for both injection molding processes. Moreover, it is unable to distinguish the stiffness difference observed for beams fabricated using the two different injection molding processes. This limitation indicates that a multi-scale model considering the phase property and the microstructure may be necessary to obtain more accurate predictions at both coupon and part levels.

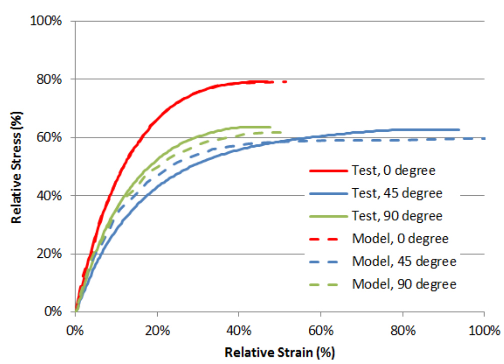


Figure 6. Comparison of predicted results of orthotropic model without failure and dogbone tension test at three angles

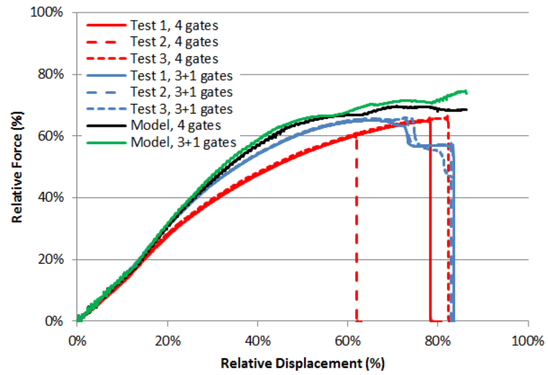


Figure 7. Comparison of predicted results of free boundary orthotropic model without failure and beam flexure test

4. Digimat® Multi-scale Modeling Method

Glass fiber and nylon PA66 matrix are considered as two phases in Digimat® multi-scale model. Glass fiber is described by an elastic model and nylon matrix behavior is represented by an elasto-plastic model. An experimental determination of the fiber orientation at the center of the plaque was done by extracting the orientation from tomography images taken through the thickness. Fiber aspect ratio and skin core effect of fiber volume are taken into account to generate a Representative Volume Element (RVE) composed of multilayer microstructures. The RVE is loaded at 0°, 45°, and 90° with respect to the primary flow direction. The matrix elasto-plastic parameters are calibrated by fitting the multi-scale model results to the dogbone tension test data.

The calibrated Digimat® multi-scale model is coupled with Abaqus to simulate dogbone tension test and beam flexure test. Fig 8 compares the multi-scale model prediction with the dogbone tension test data. Although the model predicts stiffer behavior for 0° loading and softer behavior for 90° loading compared to the measured data, the discrepancy between model and test data for 3 loading cases is balanced by the calibration procedure and there is good agreement overall for loading at 3 different angles. Fig 9 shows a large improvement of beam behavior prediction of multi-scale model compared to phenomenal orthotropic model for both 4 gates and 3+1 gates injection processes. The multi-scale model is able to detect the injection process influence on the beam behavior and capture the beam stiffness very well.

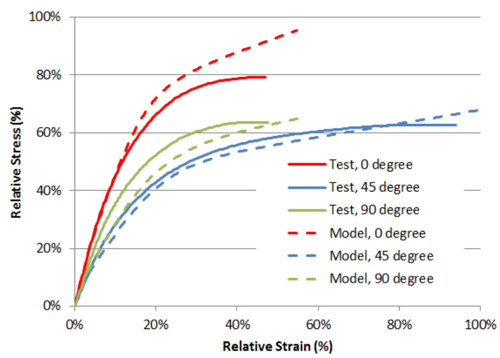


Figure 8. Comparison of predicted results of Digimat® multi-scale model without failure and dogbone tension test at three angles

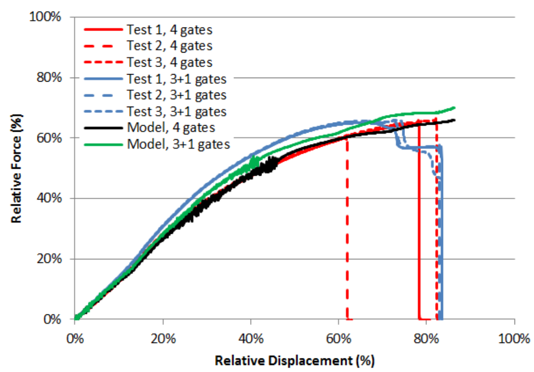


Figure 9. Comparison of predicted results of free boundary Digimat® multi-scale model without failure and beam flexure test

Furthermore, a strain based Tsai-Hill 3D transversely isotropic failure model offered by Digimat® is explored to add failure prediction to the multi-scale model. The failure parameters are calibrated by matching the failure strain of dogbone tension test at three angles, shown in Fig 10. The overall failure prediction at coupon level is good, except it is a little over-predicted for the 0° loading and somewhat under-predicted for the 45° loading. The same failure parameters are applied to the simulation of beam flexure test. Because the Tsai-Hill failure criterion's ability to fully describe failure under various loading modes is limited and the failure parameters are calibrated from only the uniaxial tension test, the predicted failure shown in Fig 11 underestimates the loading peak of the beam whose body experiences complex states of stress. Fig 12 compares the observed and predicted beam failure location for both injection processes. The 4 gates injection beam fails across the middle section, but the predicted failure occurs at the beam flange and rib and it doesn't cross along the bottom of the beam. The observed 3 gates injection beam failure is away from the middle, but the predicted failure location is at the middle. Both force-displacement curve and failure location comparison suggest that a different failure criterion is required to improve the failure prediction for the short fiber composites.

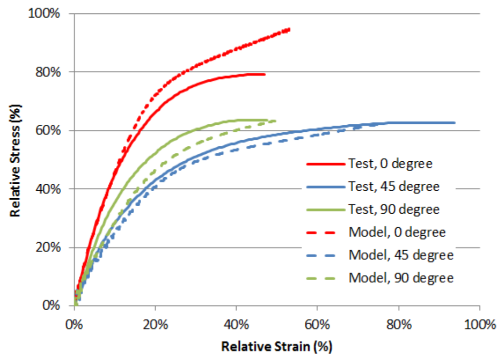


Figure 10. Comparison of predicted results of Digimat® multi-scale model with failure and dogbone tension test at three angles

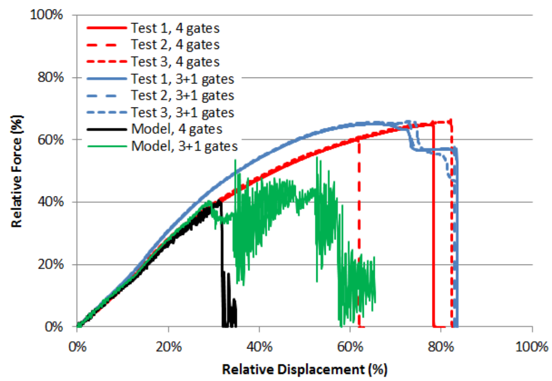
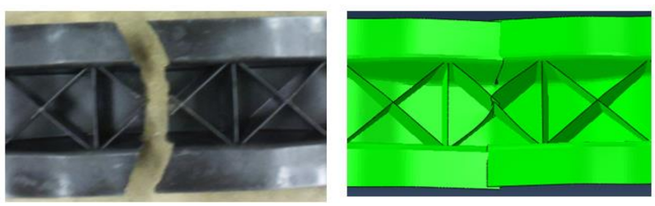
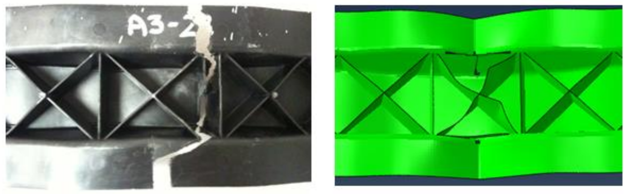


Figure 11. Comparison of predicted results of free boundary Digimat® multi-scale model with failure and beam flexure test



(a) 4 gates injection



(b) 3+1 gates injection

Figure 12. Beam failure location comparison of experiment and Digimat® multi-scale model

5. Uncoupled Digimat® with Abaqus Model

A failure criterion with the capability to define failure for different loading modes, offered by Abaqus®, is selected to improve the failure prediction of short fiber composites. In order to combine the advantage of Digimat® multi-scale modeling with Abaqus built-in failure modeling, in-house scripts and Abaqus User subroutine (Abaqus®, Section 1.2) are developed to transfer the Digimat® multi-scale model parameters into Abaqus material definition. Thereafter, the Abaqus failure criterion is added to the uncoupled Digimat® multi-scale model. Considering the extended capability of the Abaqus®s failure, the failure parameters are calibrated not only by the dogbone tension failure but also by the beam failure.

The uncoupled Digimat® with Abaqus model prediction for dogbone and beam are summarized in Fig 13 and Fig 14 respectively. Although the model still under-predicts 45^0 degree tension failure, the beam failure prediction is largely improved for both 4 gates and 3+1 gates injection beams. The predicted and actual beam failure locations are compared in Fig 15. The failure location and the contour of fiber orientation tensor in beam width direction are presented together in Fig 16. The model predicts the same failure location for 4 gates injection as the actual beam and the location is consistent to the beam weld line at the middle. The 3+1 gates injection beam failure location is between the loading location and the weld line, while the model predicts failure along the weld line at the bottom of the beam. Although there is still a discrepancy between predicted and actual failure location for 3+1 gates injection beam, the model captures the weld line effect and predicts the failure location away from the middle. Furthermore, the model is then validated by the simulation of beam test with clamped boundary, showing comparison results in Fig 17. Both the model and test display similar stiffness for two injection processes and a higher breaking peak of 3+1 gates injection beam than the 4 gates injection beam.

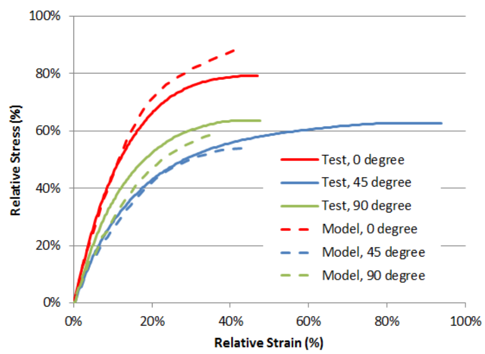


Figure 13. Comparison of predicted results of uncoupled Digimat® with Abaqus model and dogbone tension test at three angles

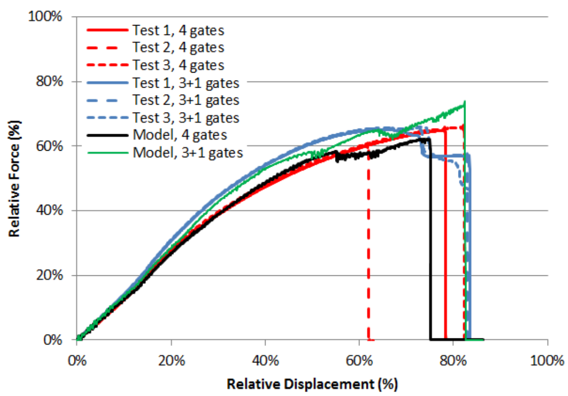
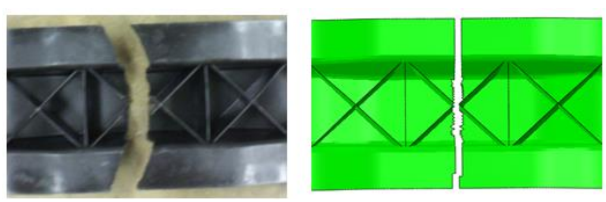
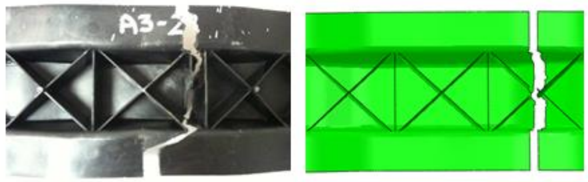


Figure 14. Comparison of predicted results of free boundary uncoupled Digimat® with Abaqus model and beam flexure test

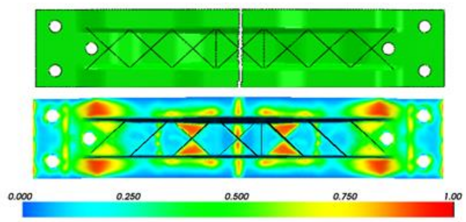


(a) 4 gates injection

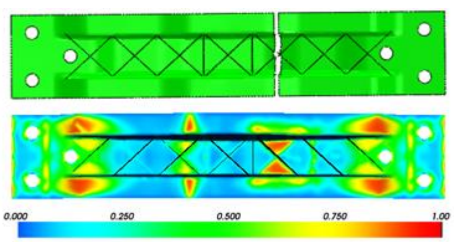


(b) 3+1 gates injection

Figure 15. Beam failure location comparison of experiment and uncoupled Digimat® with Abaqus model



(a) 4 gates injection



(b) 3+1 gates injection

Figure 16. Beam failure location and orientation tensor in beam width direction

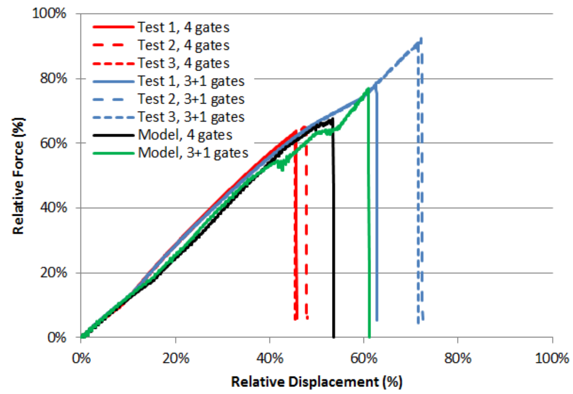


Figure 17. Comparison of predicted results of clamped boundary uncoupled Digimat® with Abaqus model and beam flexure test

6. Summary and Conclusion

In order to describe the behavior of short fiber reinforced composites, a solution is implemented by uncoupling and transferring Digimat® multi-scale model features to Abaqus with improved failure criterion. The robustness of the uncoupled Digimat® with Abaqus s model is challenged by predicting the stress-strain behavior with failure for composites at coupon and component level with different injection molding processes and different testing boundary conditions. Some discrepancy between model prediction and measured data may be caused by the lack of orientation information across the whole dogbone during the model calibration.

The uncoupled Digimat® method offers more options for failure definition. In addition, the method can be leveraged to develop other short fiber composites for failure prediction of auto part design in various applications.

7. References

1. Volgers, P, and Kuhlmann, H., and Zhang Z., "New Constitutive Model for Woven Thermoplastic Composite Materials," SIMULIA Community Conference, Berlin, Germany, 2015.
2. Digimat Documentation, Release 6.0.1 – May 2015, E-Xstream Engineering as MSC Software Company, Mont-Saint-Guibert, Belgium.
3. Abaqus Users Manual, Version 6.14-2, Dassault Systémes Simulia Corp., Providence, RI.
4. Abaqus User Subroutines Reference Guide, Version 6.14-2, Dassault Systémes Simulia Corp., Providence, RI.