Application and CAE Simulation of Over Molded Short and Continuous Fiber Thermoplastic Composite

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Abstract

In the field of structural design, from aerospace and automotive to consumer packaging, numerical structural analysis using the finite element method (FEM) is becoming ever more important to accurately predict the performance of the considered part. In a highly competitive market, industries are demanding higher performance, improvements in fuel efficiency, increased recycling and greater safety, whether this is an airplane wing or mineral water bottle. In response to the above factors, there has been a significant increase in the application of composites. Today, finite element simulations are used extensively in the design and assessment by virtually all mayor industries. Finite element analysis (FEA) has become an integrated tool in this design and optimization.

In this paper, beams constructed from over molded Short Fiber Reinforced Thermoplastic on Continuous Fiber Reinforced Thermoplastics are described. One of the challenges is accurate CAE simulation of the static and dynamic behavior of the part. Model data are validated through correlation between coupon and sub-system physical tests, and further verified with results from quasi-static and impact tests. Physical test on beams confirmed good correlation between test and Finite Element Analysis.

Introduction

Composites play an important role in many applications such as automotive and aircraft, sport goods and mechanical and civil engineering applications. There are a number of advantages in comparison with metals and other structural materials such as light weight, high stiffness, high strength to weight ratio and energy absorbing properties. There are also disadvantages such as complex design rules and failure analysis.

The demand for numerical simulation is increasing rapidly. Finite element simulations are used extensively in vehicle design and crashworthiness assessments by virtually all car manufacturers. These allow car makers to reduce vehicle design cycles and avoid the high cost associated with experimental testing. Crash simulations have to be able to describe the different behaviors of these materials across a range of stresses and deformations, from elastic deformation up to large deformations at failure. In this paper, beams constructed from over molded Short Fiber Reinforced Thermoplastic on Continuous Fiber Reinforced Thermoplastics are described. One of the challenges is accurate CAE simulation of the static and dynamic behavior of the part. Model data is validated through correlation between coupon and sub-system physical tests, and further verified with results from quasi-static and impact tests. Physical test on beams confirmed good correlation between test and Finite Element Analysis.

Material Characterization

Composite materials are generally orthotropic and have complex mode of failure. Therefore, a large number of strength and elastic properties must be determined for an accurate material characterization. Material testing started with quasi-static experiments, such as tensile, shear and compression tests. Quasi-static strain rates were in the range of 10^{-4} - 10^{-3} s^{-1}. Materials were then tested under dynamic loading, using a servo-hydraulic test machine, drop tower impact test and/or a Split Hopkinson Pressure Bar.

In this paper, short fiber reinforced thermoplastics validation will be covered briefly, and the work will mainly be focused on the characterization and validation of continuous fiber reinforced thermoplastic and over molded short and continuous thermoplastic composites.

Material Testing

In order to determine the parameters for the constitutive models and to verify the models, extensive material testing was conducted at the coupon level, as well as on components.

For the short fiber reinforced thermoplastic material, coupons cut from injection molded plaques were tested under quasi-static and dynamic loading. This included testing for various fiber orientation, temperatures, strain rates, moisture content and fiber content. In addition, injection molded parts were tested under different strain rates, loading and boundary conditions. Moldflow analysis of the injection molded plaques and parts were carried out, to simulate the manufacturing process. These analyses provide detailed information of the glass fiber orientation in the parts, which are then mapped to the finite element model of each part.

Some of tests that were conducted are shown in Figure 1-4.

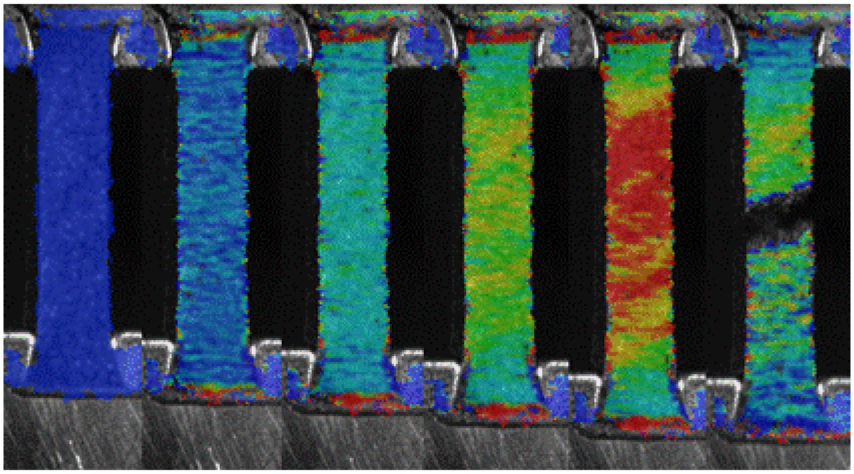


Figure 1: Strain Distribution Snapshots during High Rate Short Fiber Reinforced Thermoplastic Tensile Test

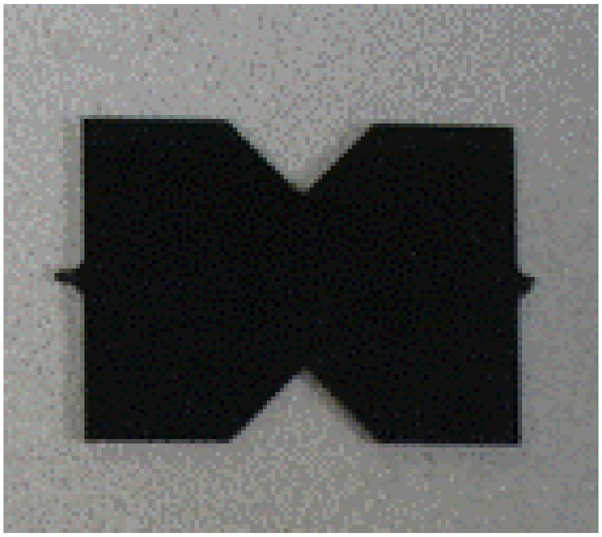


Figure 2: Short Fiber Reinforced Thermoplastic Shear Test Coupon

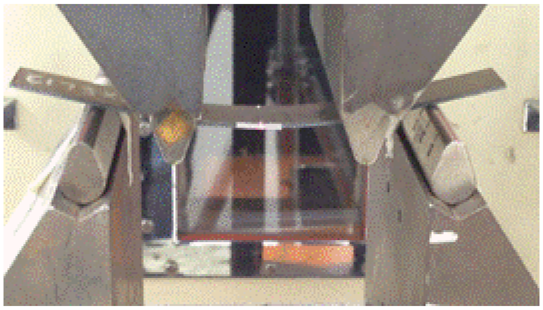


Figure 3: Short Fiber Reinforced Thermoplastic 4 Point Bending Test

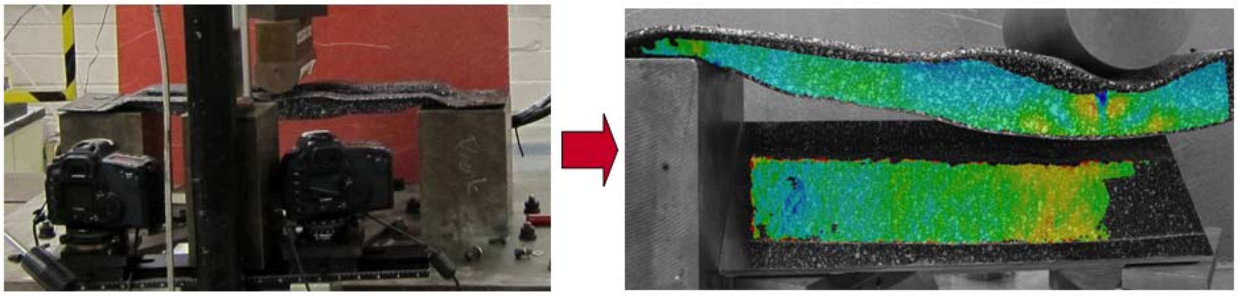


Figure 4: Short Fiber Reinforced Thermoplastic Beam Test Setup and DIC data

For the continuous fiber reinforced thermoplastic material, coupons cut from sheet were tested under quasi-static and dynamic loading. This included testing for various fiber orientation (0°, 30°, 45°,60°,90°), temperatures, strain rates, and moisture content. In addition, stamped laminate and over-molded short fiber reinforced thermoplastic over continuous fiber reinforced component were tested under different strain rates, loading and boundary conditions.

High rate tensile tests and dynamic testing on a drop tower facility were conducted to investigate the material behavior under high loading rates and develop material model parameter that capture increase in stiffness, strength and failure strain.

Example of some of the test conducted for the characterization and development of the continuous fiber reinforced thermoplastic material model are presented in Figure 5-9.

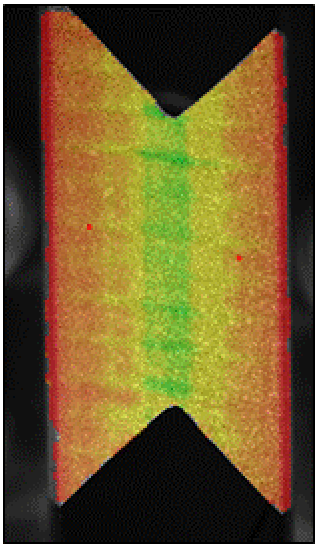


Figure 5:   Continuous Fiber Reinforced Thermoplastic Shear DIC Data

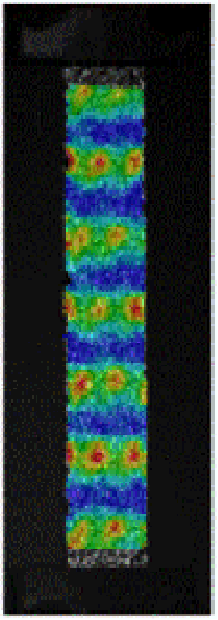


Figure 6:   High Rate Continuous Fiber Reinforced Thermoplastic DIC Tensile Data Snapshot

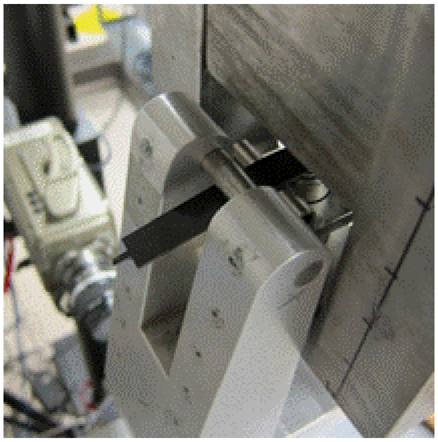


Figure 7: High Rate Continuous Fiber Reinforced Thermoplastic 4 Point Bending Test

Figure 8: Drop Tower Plaque Impact Testing

Figure 9: Drop Tower Beam Impact Test

Material Model

The experimental information is used to develop and validate the material model. Based on the mechanical characteristics obtained from the material test, the material model must be non-linear, strain rate dependent, orthotropic and include advance material damage and failure. The LS-DYNA® material card used to define this material behavior is MAT 158 [1].

For the fiber reinforced thermoplastic material MAT158 was selected as it can represent non-linear stress-strain behavior. The constitutive model is based on the theory of continuum damage mechanics [2, 3]. It is assumed that the deformation introduces micro-cracks and cavities into the material. These defects reduce the material stiffness. This is expressed through internal damage parameters, which describe the evolution of the damage state under loading und hence stiffness degradation. Five failure criteria for the fiber reinforced thermoplastic are defined: tensile and compression failure in 0° and 90° direction, as well as shear failure [4].

MAT158 incorporates strain rate effects. A viscous stress tensor is calculated on the basis of a generalized Maxwell model, where up to six terms in the Prony series expansion can be defined through their shear relaxation modulus and shear decay constant. This viscous stress tensor is then superimposed on the rate independent stress tensor

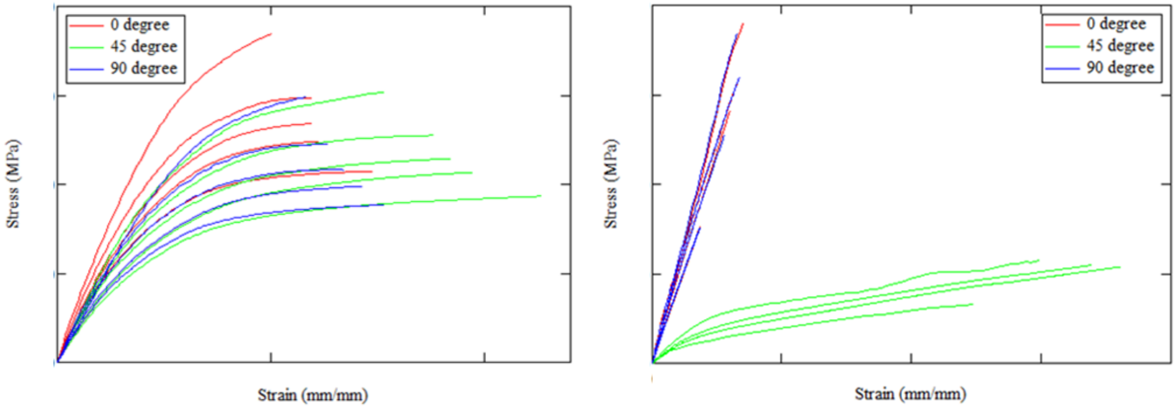


Figure 10: Tension Test Data at Different Strain Rate at Different Angles

Although short fiber and continuous fiber composite behavior are different as shown in Figure 10, the development method of Mat158 for these two materials is similar. Quasi-static coupon test data at different angles are used to characterize the quasi-static stiffness and strength of Mat158. Prony series coefficients are calibrated by high strain test data. A smooth failure surface in the transverse direction with a limiting value in fiber direction is selected for short fiber reinforced composites, while a smooth failure surface with a quadratic criterion for both the fiber warp and weft directions is assigned to continuous fiber reinforced composites.

MAT_ADD_EROSION with estimated failure strain are added to both models. Considering the theoretical infinite large failure strain for short fiber composites under compression, the compression damage parameters SLIMC1 and SLIMC2 are assigned to be 1. The damage parameters for continuous fiber composites are calibrated by tests with various loading conditions to obtain a robust material model.

Simulation

The analytical models are compared to three levels of tests: material coupon test, material plaque impact test and three point bending beam test. Initial material model development and verification starts with reproducing experimental material stress/strain curves, bending load vs. deflection, and panel deflection. Beam prediction under different boundary condition and loading speeds is used to verify material model and to further improve damage and failure predictions.

The following three sections present some of the simulations that were carried out for the development and validation of the material models.

Short Fiber Reinforced Thermoplastic

A 3D finite element model is created using LS-DYNA to simulate high strain rate tensile test as shown in Figure 11. Four rigid pieces contacting specimen's shoulders represent the grip constraint. Two pieces on one side are fixed and the other two pieces are moved at a constant velocity in length direction. The developed fiber orientation model is assigned to the specimen for FEA simulation. The comparison between the measure and calculated stress-strain curves for three angles and five test speeds are summarized in Figure 12. The model predicts the rate dependent effect very well

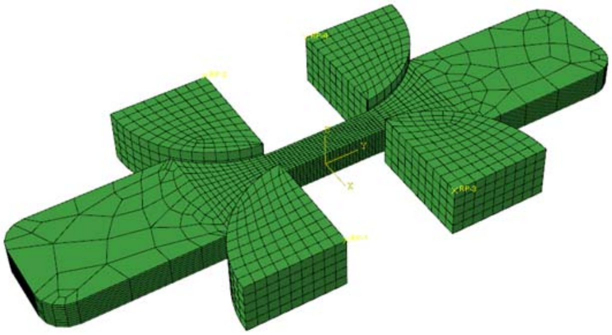


Figure 11: 3D FE Model of Short Fiber Composites Tensile Test

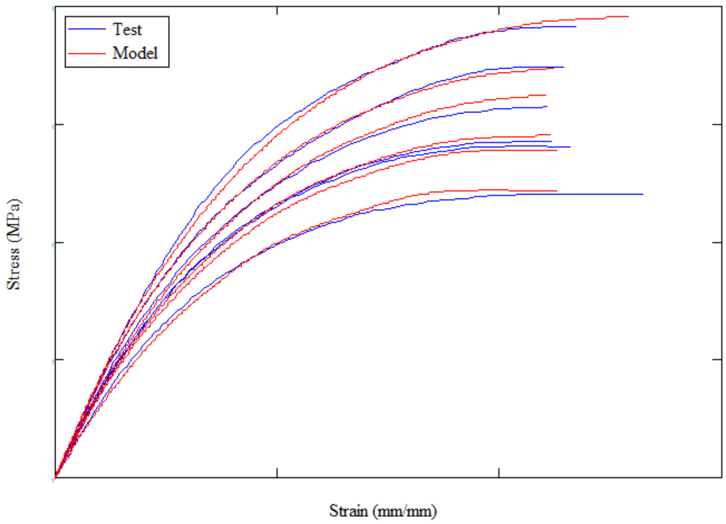


Figure 12: Stress-strain Comparison of Test Data and Model Results for Short Fiber Composites

A three point bending test is conducted with the beam placed on two supports and loaded by an impact nose. The velocity of the nose is controlled and the force is measured by a load cell installed on the impact nose. Beams are tested at both quasi-static and dynamic loading with various boundary conditions for model validation. The supports and the impact nose are modeled as rigid bodies. The same experimental boundary condition and loading speed are applied in the beam model.

Figure 13 shows the comparison of force-displacement curve between test and model for one of boundary conditions. The model captures the stiffness and strength very well at both quasi-static and dynamic loading. Figure 14 compares the predicted failure location with the actual failure of tested beam. The good agreement between the model prediction and test data for beams with various boundary conditions validates the model robustness.

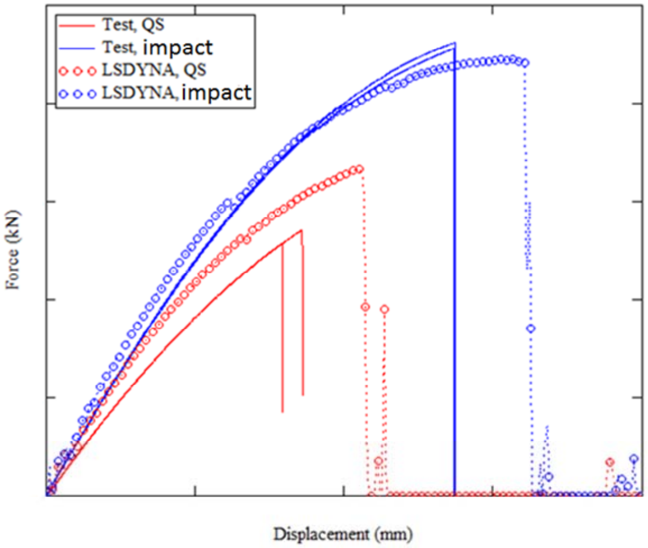


Figure 13: Comparison of Measured and Predicted Force-displacement curve of Short Fiber Composite Beam

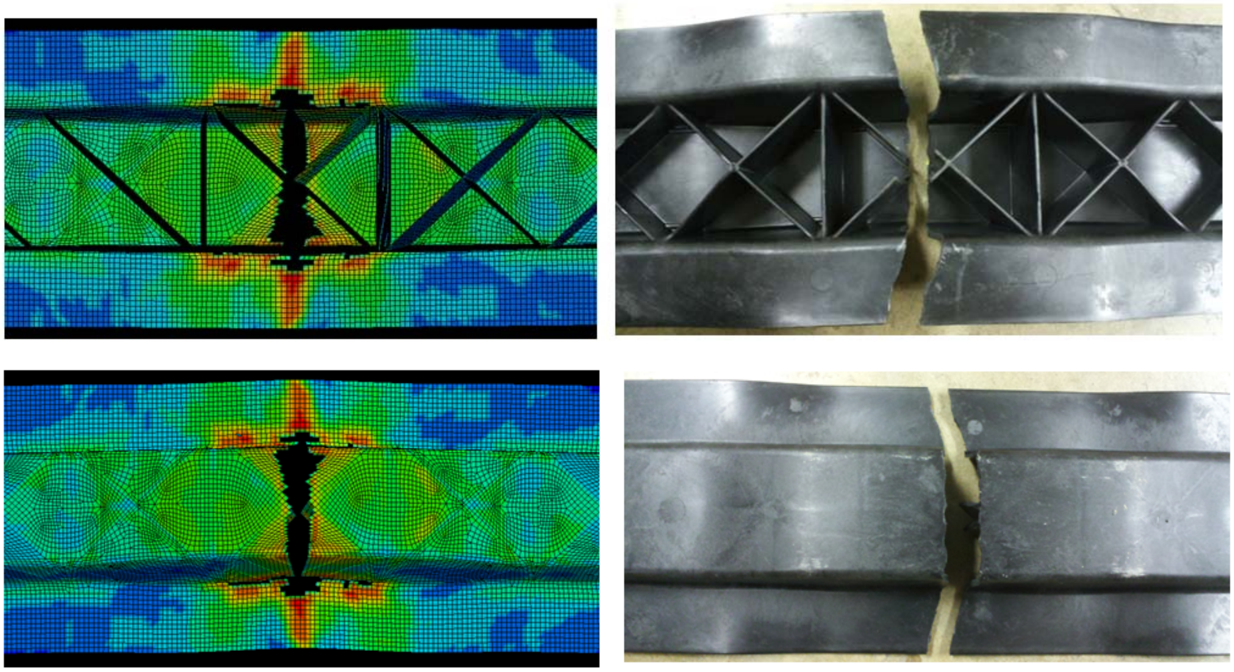


Figure 14: Comparison of Failure location at Front and Back of Short Fiber Composite Beam

Continuous Fiber Reinforced Thermoplastic

As it was indicated previously, a series of tests under different loading conditions, strain rate and sample geometry were conducted to support the development of the material model. Figure 15 compares the force-displacement response of the drop tower model to the experimental results at three different impact speeds. Model data correlates well to experimental data, with similar peak load levels.

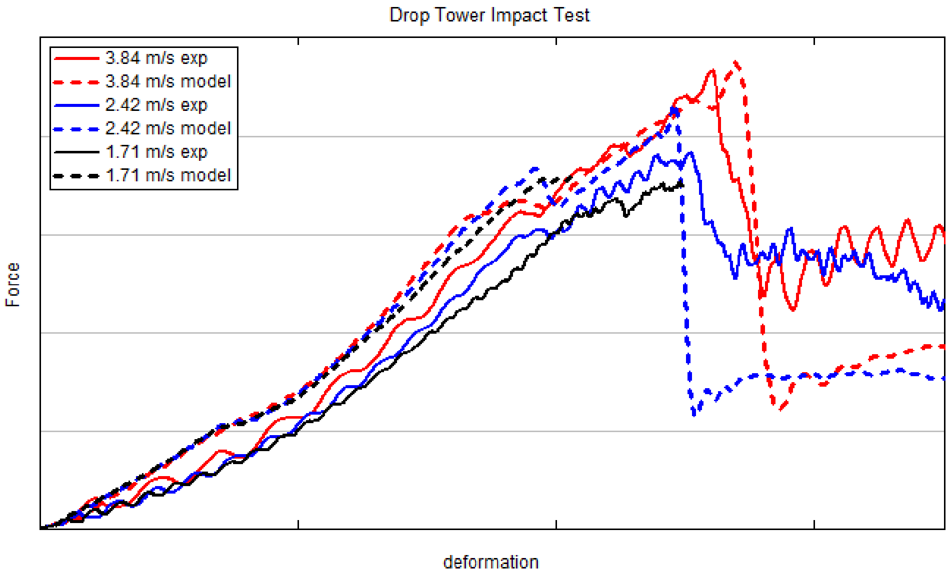


Figure 15: Drop Tower Testing vs Model Prediction

A visual comparison, of model damage and experimental sample damage is shown in Figure 16. The crack measured on the drop tower samples is approximated 22 mm x 26.5 mm. Model impacted at same speed predicts a 27 mm crack in both direction

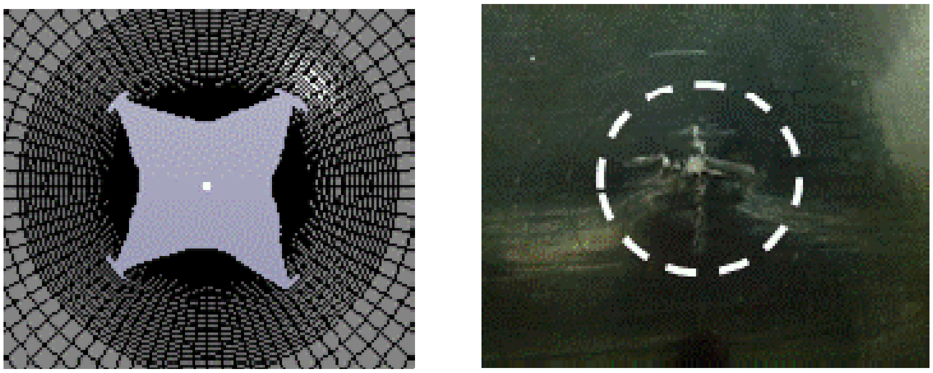


Figure 16: Drop Tower Model Damage Prediction and highlighted Damaged Area of Tested Sample

Drop tower beam impact test were conducted under different impact speeds and boundary conditions. Figure 17 shows experimental data for three beams impacted at a similar speed and the predicted response of the FEA simulation. The predicted peak force match test well, but model force response stayed flat after peak force and did not drop as observed on the test.

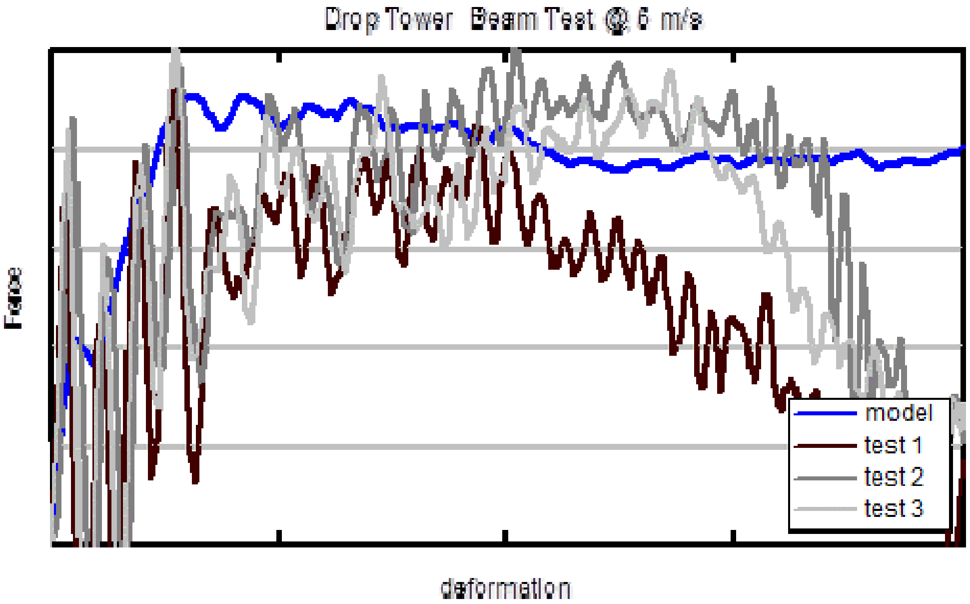


Figure 17: Simulation-Test Comparison of Drop Tower Testing Beam Impact Response

In addition to validating the material model by comparing the force-displacement response of test and simulation at different impact speed, a visual inspection of the beams is conducted and failure and damage area are identified and compared to model predictions. Figure 18 shows one of the simulation and test cases from our program. It can be observed that the location of the damage and intensity of it are very comparable between test and simulation.

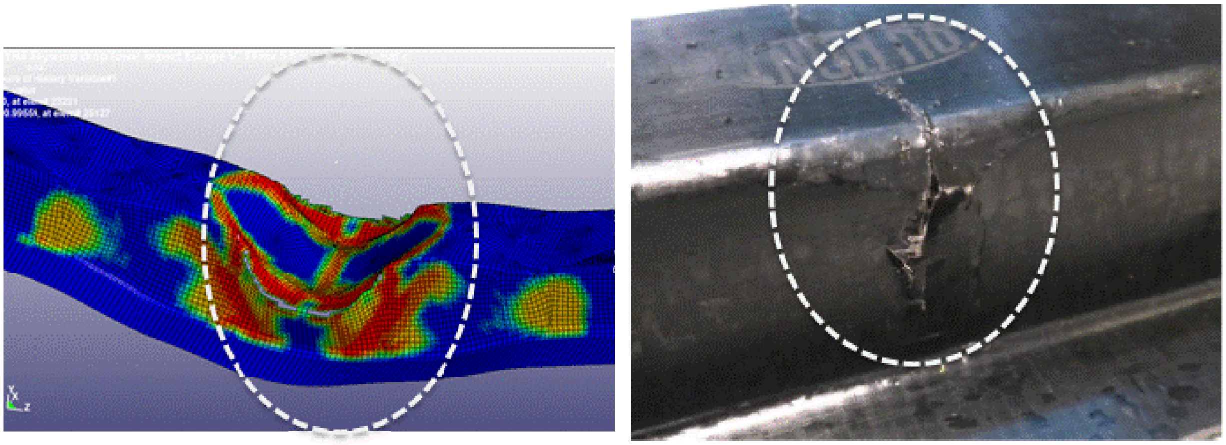


Figure 18: Visual Damage Comparison between Simulation and Experiment after Drop Tower Impact Test

Over Molded Short Fiber Reinforced Thermoplastic over Continuous Fiber Reinforced Thermoplastic

An over-molded beam manufactured using DuPont hybrid material technology is composed of a stamp-formed woven laminate layer over-molded with a short fiber reinforced thermoplastic. An FE model is generated based on actual geometry. Two layers of shell elements sharing the same nodes are employed to represent laminate layer and injection over-molded layer. The mold filling simulation is executed to obtain the short fiber orientation for injection molded layer, while the woven warp direction is assigned aligned in the beam length direction. The developed material models for short fiber and woven fabric composites are assigned to corresponding layers.

Three point bending tests with various boundary conditions at constant loading speed from quasi-static to slow impact loading are conducted. The corresponding experimental boundary condition and loading speed are applied in the beam model. Figure 19 shows the comparison of force-displacement curve between three point bending test and model. The model has a very good prediction of both peak load and dissipation energy after peak load.

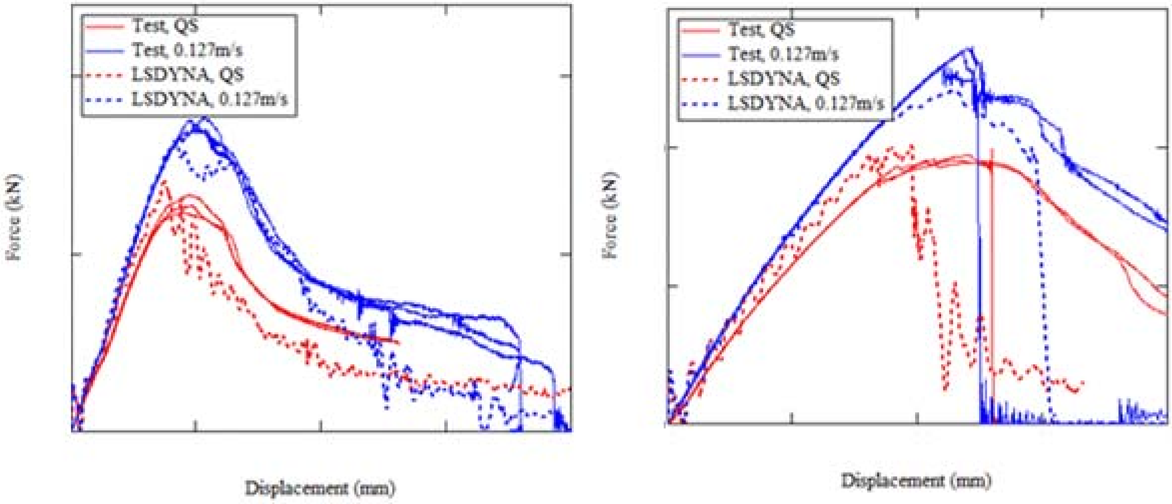
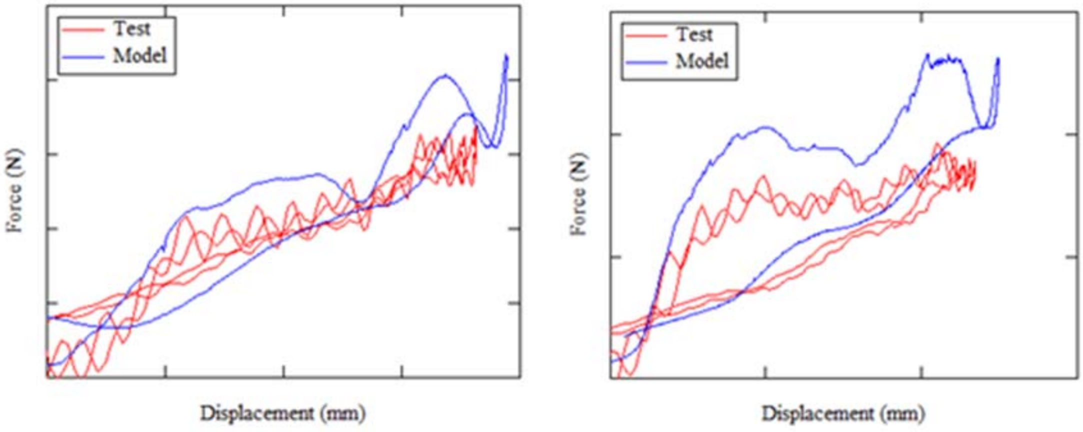


Figure 19: Comparison of Measured and Predicted Force-displacement curve of Over Molded Beam with different Boundary Conditions at Quasi-static and Slow Impact

In order to further challenge the model, drop tower tests are conducted on over molded beam with different drop heights. The model is created based on actual testing condition. Figure 20 shows the comparison of force-displacement curve between drop tower test and model. There is no damage at lower drop height and there is some damage at higher drop height. The prediction is consistent to the experimental observation. Figure 21 shows the good agreement of failure location at higher drop height. The model over predicts the higher load peak than the measured data at higher drop height. This is partly related to the rate dependent effect of the model. Further material characterization at higher strain rate can provide a more complete set of data to improve the model.



(a) Lower drop height (b) Higher drop height

Figure 20: Comparison of Measured and Predicted Force-displacement curve of Drop Tower Test on Over-Molded Beam

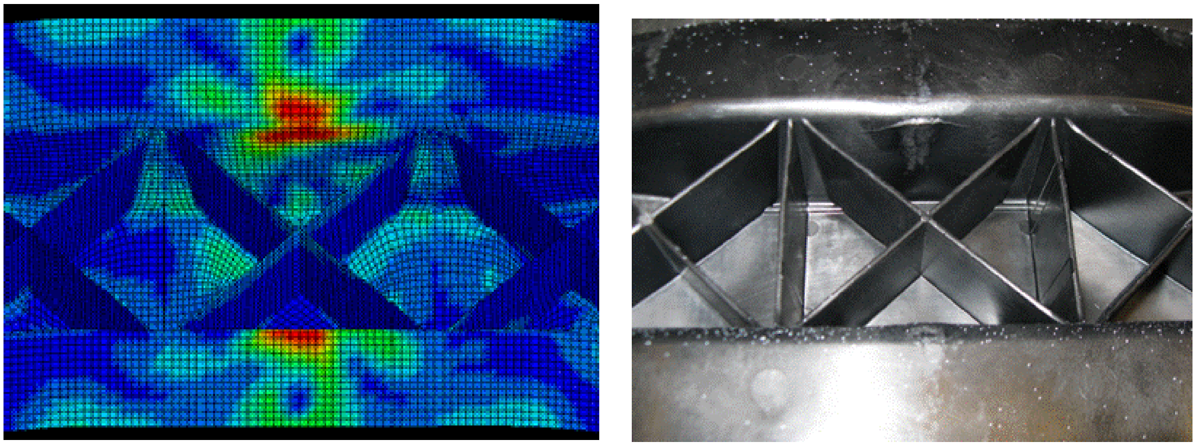


Figure 21: Comparison of Failure Location at Front and Back of Over-molded Beam at the Higher Speed

Conclusions

Material models to predict deformation and failure for short fiber reinforced thermoplastic and continuous fiber reinforced thermoplastic has been successfully developed using Mat158. A number of standardized test and customized test were carried out to determine the various parameters in the material model card including damage and failure. A number of examples are shown to verify and validate the material model

The following investigation and improvements are planned for future studies:

1. Drop tower impact test on over molded short fiber reinforced over continuous fiber reinforced thermoplastic plaques
2. Run tests and simulations for other short and continuous fiber reinforced thermoplastic materials
3. Validate Mat158 capability to predict fiber glass and well as carbon composites.

References

[1] LS-DYNA Keyword Manual

[2] Matzemiller, A.; Lubliner, J.; Taylor, R. L.; A Constitutive Model for Anisotropic Damage in Fiber-Composite, Mechanics of Materials 20 (1995) 125-152

[3] Schweizerhof, K.; Weimar, K.; Muenz, Th.; Rottner, Th.; Crashworthiness Analysis with Enhanced Composite Material Models in LS-DYNA- Merits and Limits; LS-DYNA World Conference, 1998, Detroit, Michigan, USA

[4] Sadowski T.; Multi-scale Modeling of Damage and Fracture processes in Composite Materials; International Centre for Mechanical Sciences; Courses and Lectures – No. 174