Predictive Models for Integrated Manufacturing and Structural Performance of Carbon Fiber Composites for Automotive Applications

Venkat Aitharaju
General Motors

2016 Annual Merit Review
June 7, 2016

Project ID: LM102

Overview

Timeline

- Project Start Date: May 1, 2015
- Project End Date: April 30, 2019
- Percent Complete: 12%

Budget

- Total project funding
  - DOE Share: $6,000,00
  - Contractor Share: $2,571,253
- Funding received in FY15 :
  - DOE Share: $184,950
  - Contractor Share: $79,264
- Funding for FY16:
  - DOE share: $1,716,792
  - Contractor share : $735,769

Barriers

A. ***Manufacturing Technology:*** Stochastic manufacturing simulation tools to predict the outcome within 15% of experimental results to reduce cost.

B. ***Performance Technology:*** Stochastic structural performance simulation to predict the outcome within 15% of experimental results to optimize design.

C. ***Integrated Technology:*** Integrative manufacturing and structural performance simulation tool that can be used in upfront design to deliver the required assembly performance without any trial and error.

Participants

General Motors
Continental Structural Plastics (CSP)
ESI Group, NA
Altair
University of Southern California

Relevance

Predictive Integrated Modeling Tools

- Primary deliverable: An ICME model capable of predicting stochastic manufacturing and structural performance of carbon fiber (CF) composites.
  - Reduce the cost of manufacturing of CF reinforced automotive components by eliminating trial and error through improved manufacturing simulations.
  - Design, optimize and validate the CF automotive structures virtually through improved performance modeling.
  - Reduce the lead time and cost to design and implement in large scale the structural automotive composites.
  - Enable the usage of CF composites for significant light-weighting of automobiles and thus improve fuel economy, thereby reducing the dependency on foreign oil, and lower emissions, which will reduce greenhouse gas emissions.

Cost Barrier

- Will demonstrate the ability to manufacture the automotive CF composites at no more than **$4.32** cost per pound weight saved to address the DOE 2030 targets.

Performance Barrier

- Will demonstrate the viability of CF composites to meet vehicle performance requirements while reducing vehicle assembly weight **(35% lighter)** compared to current steel design.

Relevance

Steps in implementing CF in automobiles

Current

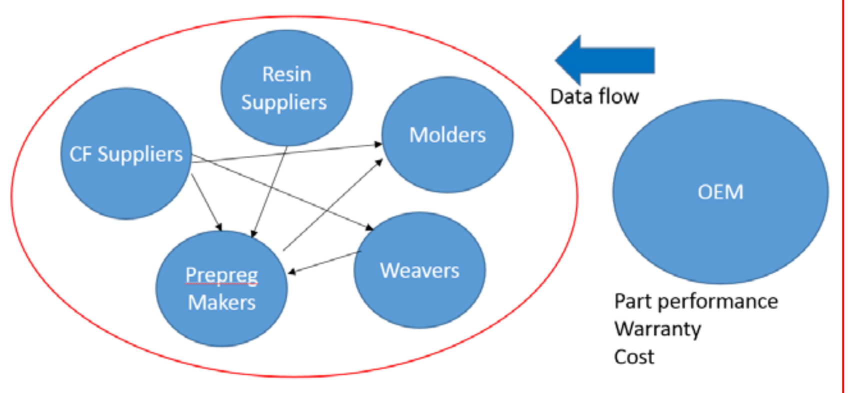
- Design.
- Selection of manufacturing process.
- Manufacturing feasibility.
- Prototype build and learn.
- Modify design and manufacturing process if needed.
- Improve prototype build and make part.
- Extrapolate to high volume manufacturing.
- Build the part, iterate to get good quality.
- Evaluate the performance and compare with requirements.
- If fail, redesign the part.

Future

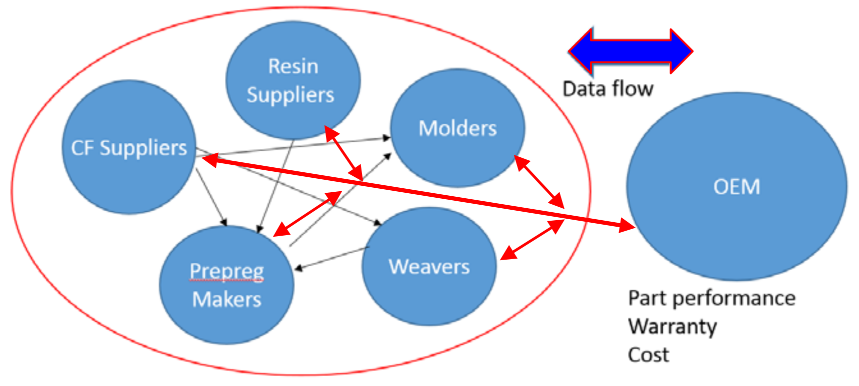
- Design.
- Virtual manufacturing simulation and improve the design for optimizing the cost.
- Include manufacturing outcome in performance simulation and further optimize the design to meet the requirements.
- Build tools, manufacture parts and check the performance

Work flow between OEM and Suppliers

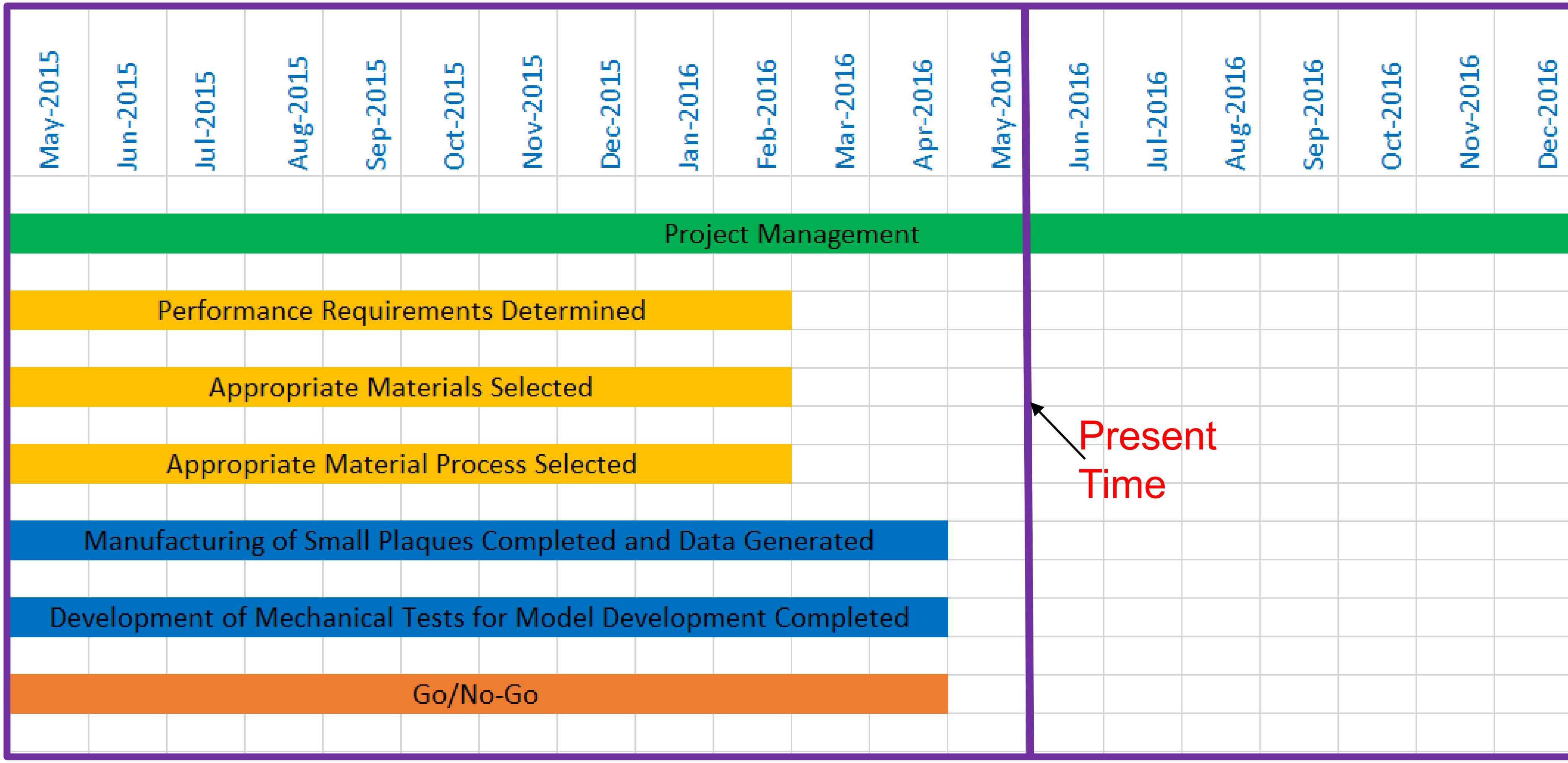
Current



Future



Milestones



All milestones for year 2016 are complete.
Go/No-Go decision was also complete.

Approach/Strategy

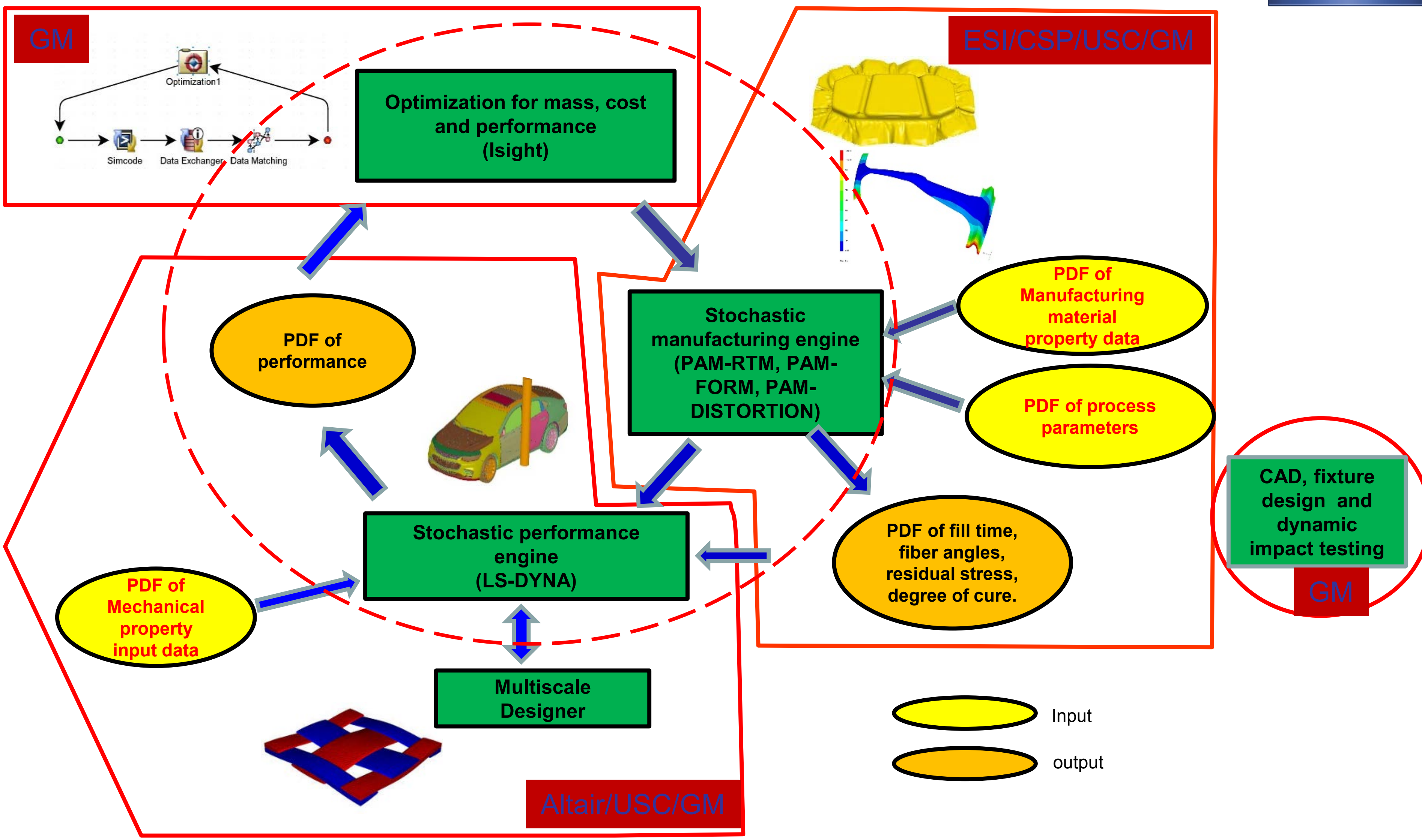
- An ICME approach to develop
  - computational methodologies and tools for predicting stochastic manufacturing.
  - computational methodologies and tools for predicting stochastic performance.
  - Integrated tools to predict the performance of an assembly.

- A team comprised of an automobile OEM, Tier 1 composite material supplier and molder, software simulation companies in the areas of composite manufacturing and performance prediction, DOE funded SciDAC institute for uncertainty quantification.

- Composite Material Supplier: Responsible for selecting materials and manufacturing processes for high volume manufacturing, provide the plaques, coupons for generating data required for model calibration and validation.
- Software Companies: Responsible for development of predictive tools for manufacturing and structural performance
- Stochastic Modeling Research Group: Develop stochastic models for both manufacturing and structural performance
- OEM : Responsible for developing and conducting experiments for models, integrating the manufacturing and structural performance tools, demonstrate the technology by design, optimize, build and test a carbon fiber automotive assembly and validate the developed models by comparing the predictions with experimental results.

Approach/Strategy

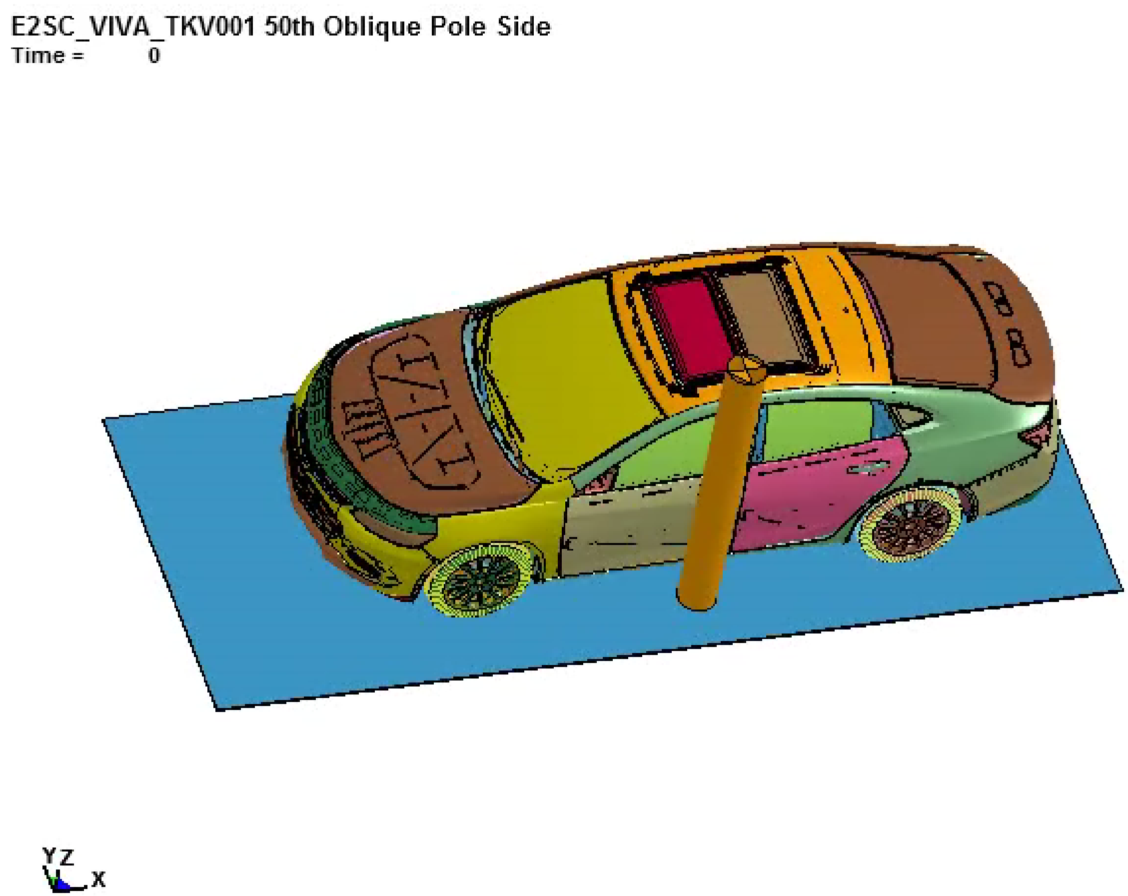
Developed a process flow of tool development



Accomplishments

FY 15 Accomplishments

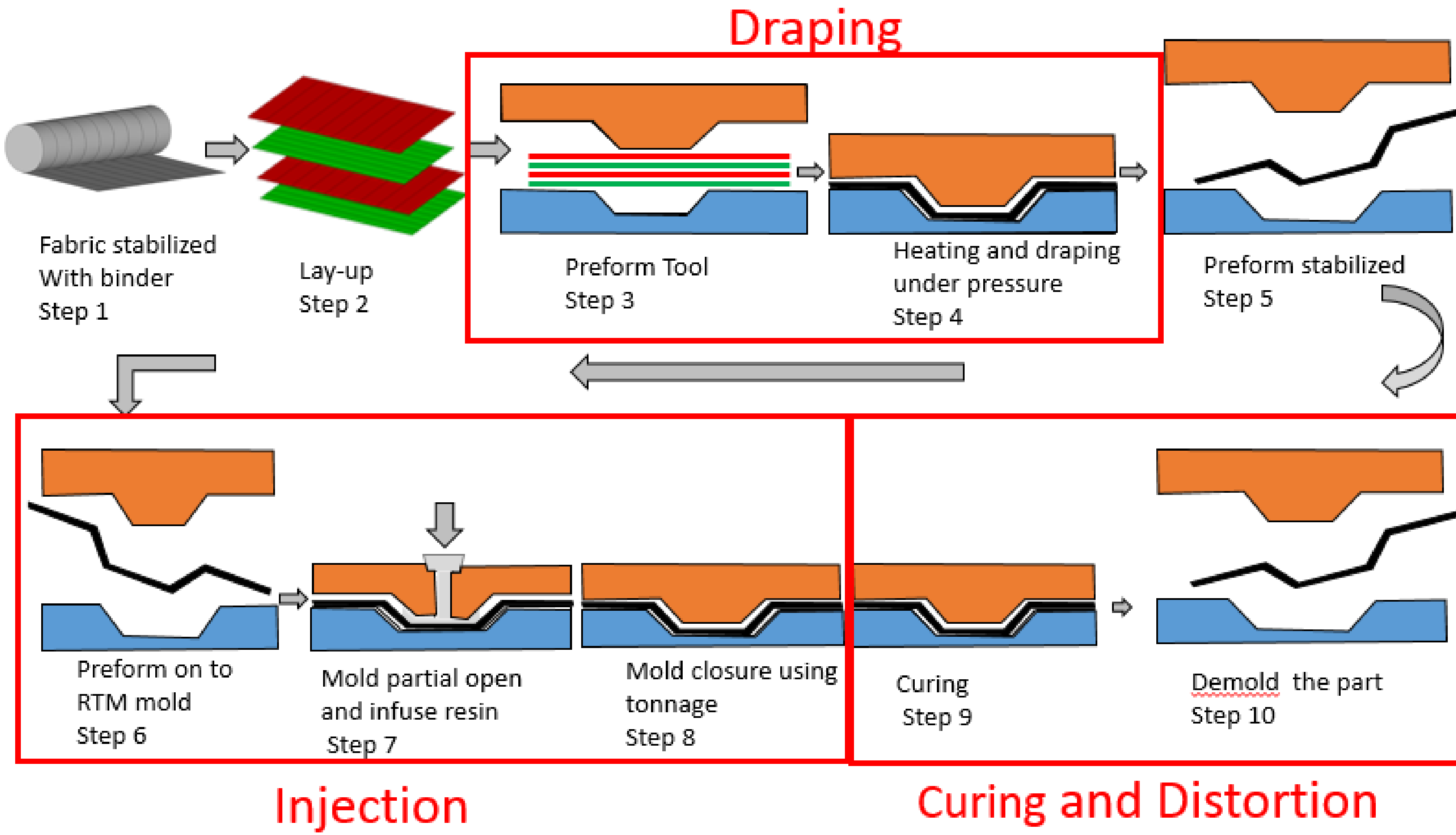
- Baseline performance requirements for the chosen automotive assembly was completed by conducting a full vehicle side impact analysis of the GM-Malibu vehicle.



Accomplishments

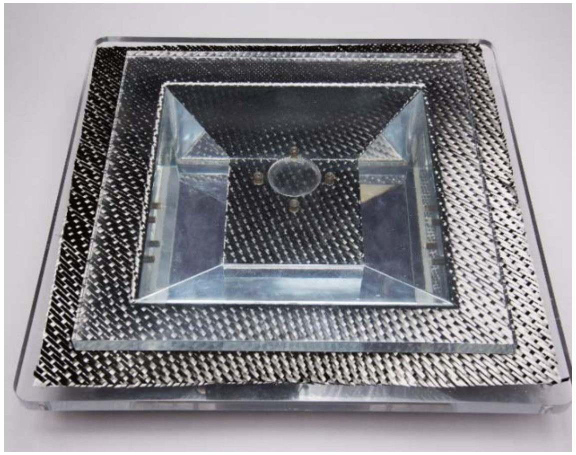
- A local analysis method was developed to enable the design, analysis and optimization, and testing for the side impact can be conducted on an assembly level rather than the entire vehicle level.
- Manufacturing processes suitable for high volume automotive manufacturing were selected – resin transfer molding (RTM, C-RTM, HP-RTM) and compression molding.
- Material systems suitable for high volume automotive manufacturing were selected and plaques were molded for material testing.17 material systems were procured and mechanically tested to rank the performance for strength, stiffness, cost, manufacturability. Material systems are from thermoset, thermoplastic with reinforcement architectures include chopped, unidirectional (with lay-up), and woven carbon fiber composites.
- Material characterization completed for all the above material systems for tension, 3-point bend, and crush.
- Crush testing was done using an Engenuity fixture

Manufacturing Process

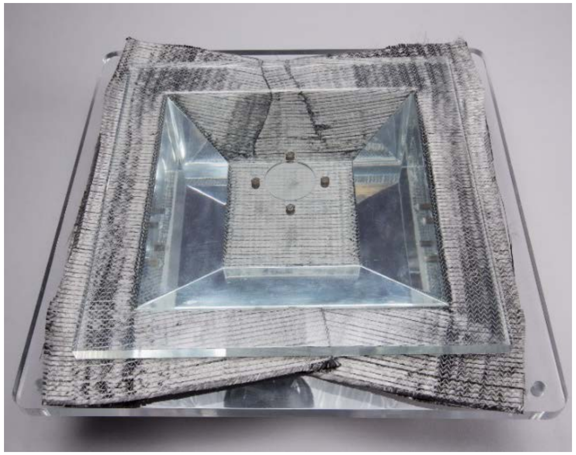


GM – Draping Tool- Experimental Data

2x2 Twill

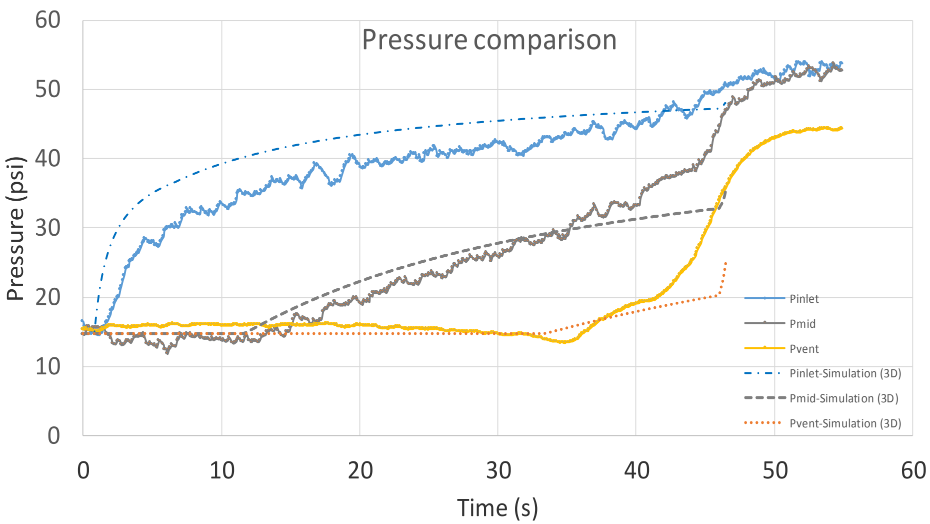


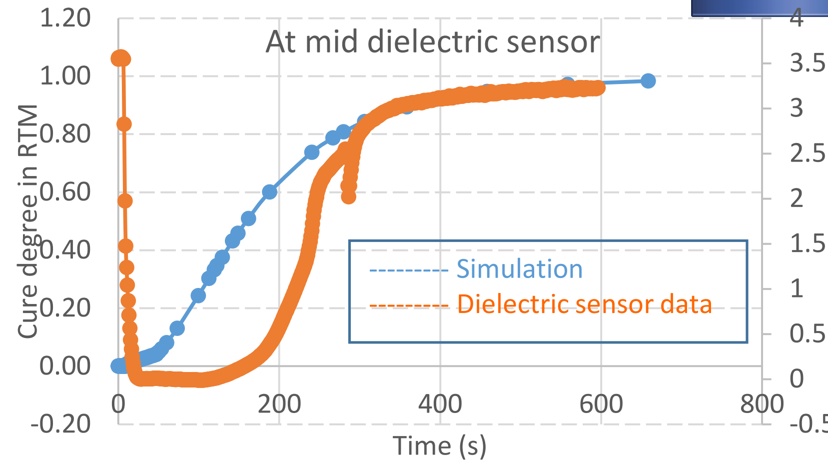
5H-Satin

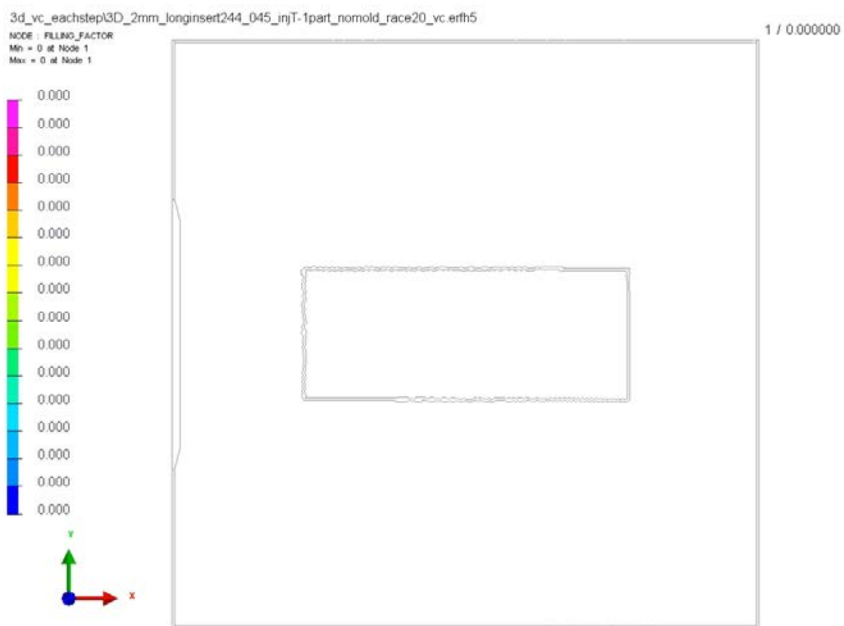


NCF

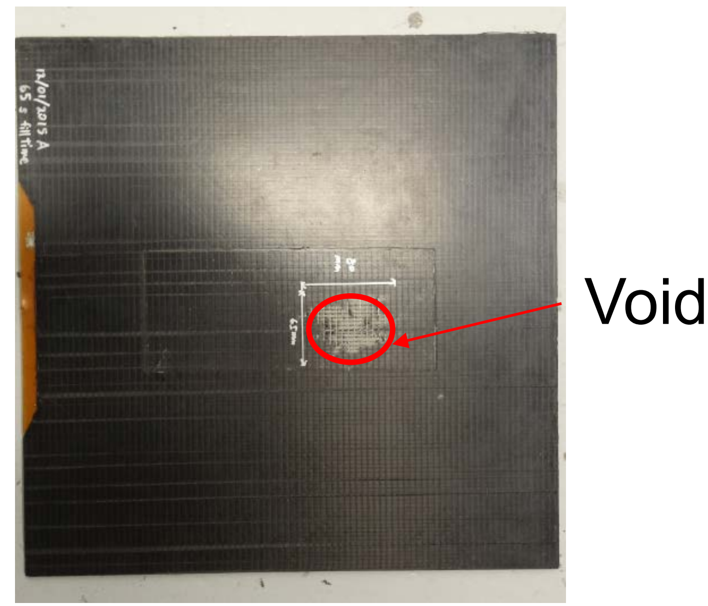
Fabric deformation experiments conducted at University of Tennessee to generate data for conducting simulations.







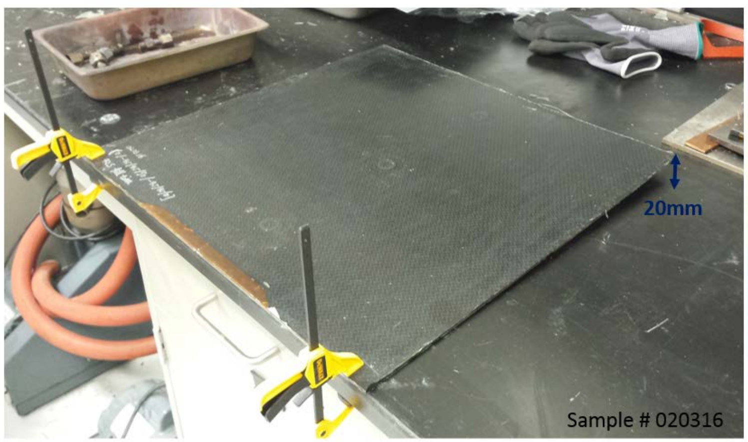
3-D flow simulation
for predicting voids



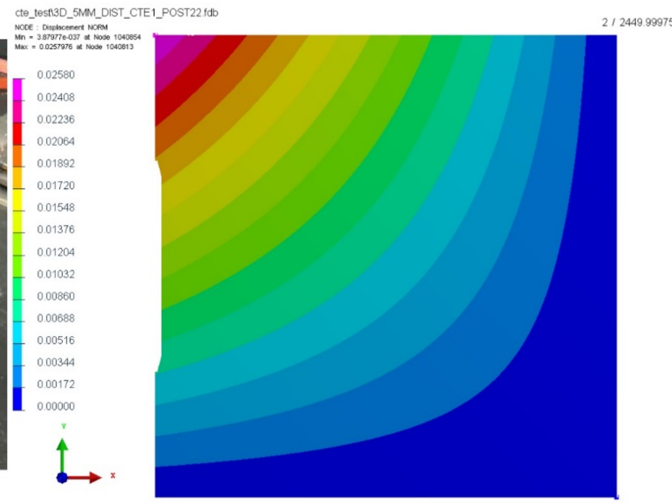
Warpage analysis

Warpage and residual stress

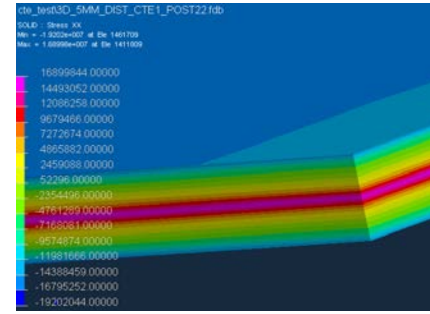
Unsymmetrical layup: 0/45/-45/90/90/45/-45/0



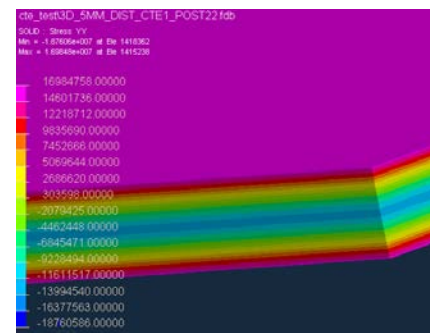
Experiment - Max. displacement
20.8 mm at the corner; upward



Prediction - Max. displacement
25.8 mm at the corner; upward



Residual stress XX

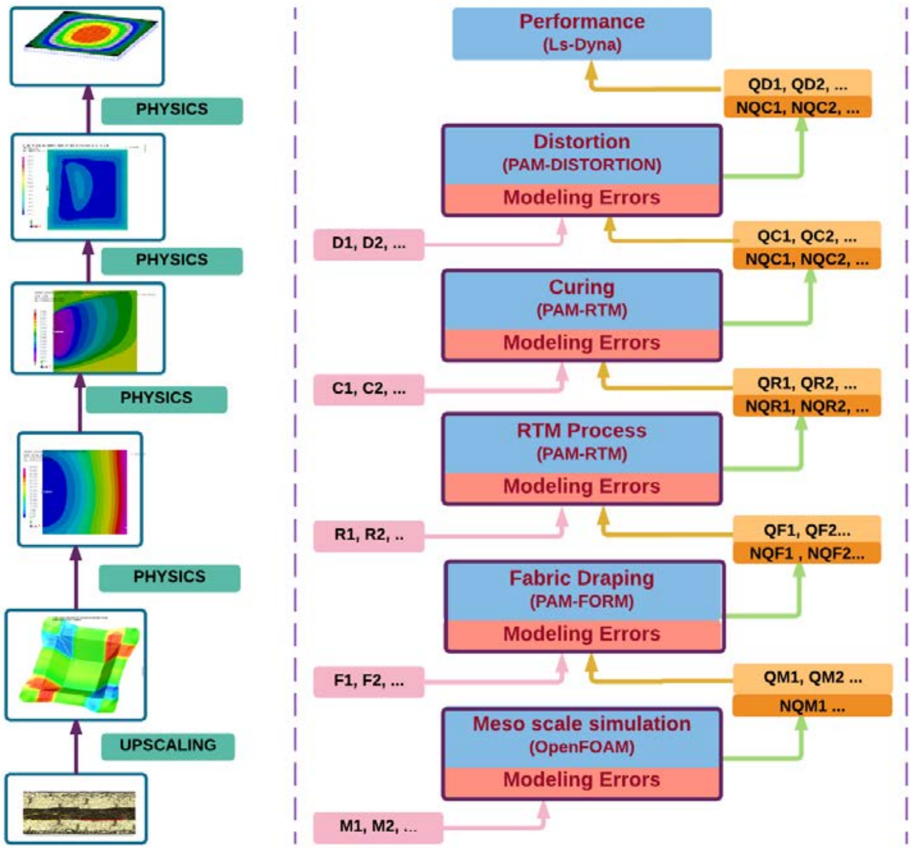


Residual stress YY

Stochastic Modeling for Manufacturing Simulations – Goals/Accomplishments

- Account for uncertainty across scales in a) geometry b) properties c) model errors d) uncertainty about uncertainty
- Better computational efficiency compared to existing Monte Carlo and Latin Hypercube method
- Developed methods need to be seamlessly integrated with deterministic codes

In this project, Polynomial Chaos Expansion (PCE) methods are used to model the uncertainty.



Framework of stochastic manufacturing tool

Structural Modeling – Goals/Accomplishments

- Multiscale Designer Framework
- Parametric unit cells
- Simultaneous calibration with multiple experiments
- Math models calibrated and validated for NCF, woven and chopped material systems

All these developments will be incorporated into Multiscale Designer software under HyperWorks and will be available for commercial use.

Multiscale Designer Framework

Stochastic Macro Solver

Analysis/
Design

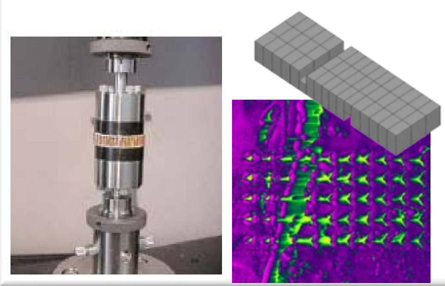
Multiscale Designer

Information
Reduction

Micro Model,
Parametric RVE library,
Import/Construct RVE,
Damage, softening,
Multiple physics
Uncertainty quantification

Model
Identification
(stochastic)

Experimental Data

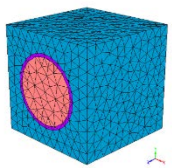


<u>Multiscale Designer Meso model</u> has fewer parameters than conventional phenomenological damage model

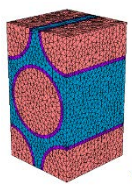
Accomplishments – Structural Modeling (Parametric Unit Cells)

Existing in Multiscale Designer

Fibrous

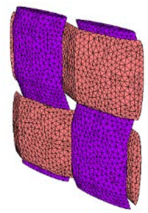


Square Lattice

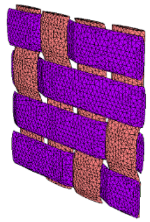


Honeycomb Lattice

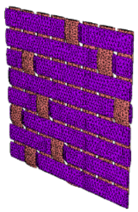
Woven



Plain Weave



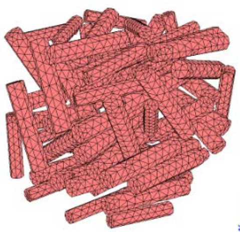
4 Harness Weave



8 Harness Weave

Random

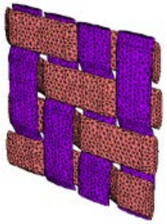
Chopped 2D



Chopped 3D

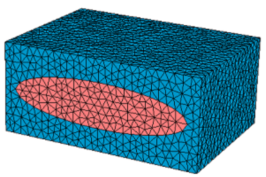
Developed under the project

Woven



2 x 2 Twill Weave

NCF

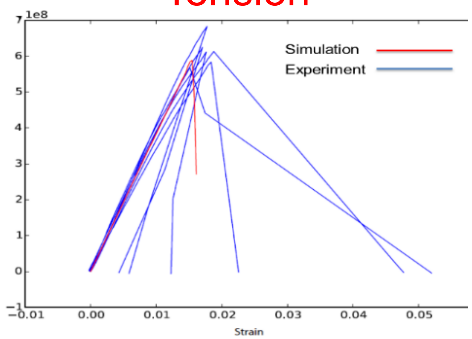


Accomplishments – Structural Modeling (NCF Composites)

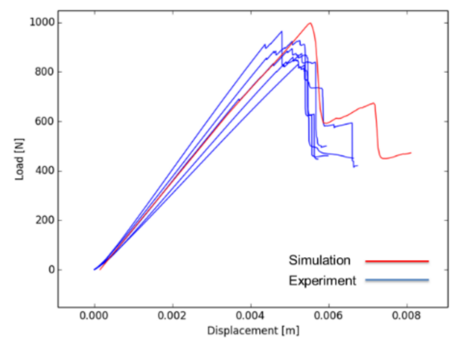
- Three material systems – NCF, woven and chopped.
- Validation of math tool for tension, three-point bend test and crush

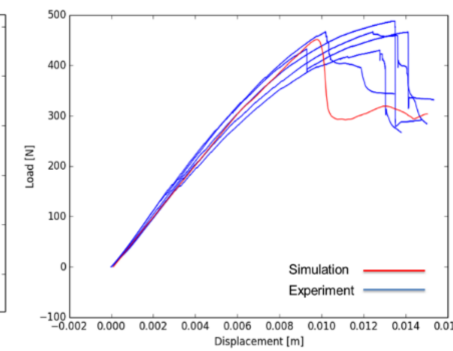
Multiscale modeling results for NCF

Tension

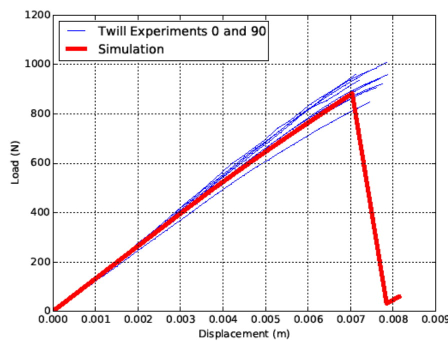


3-Point bend test – 0 deg and 90 deg

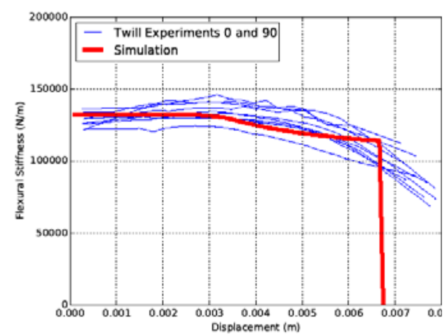




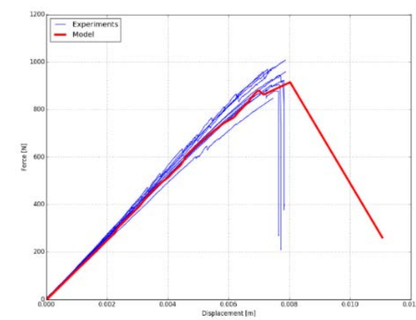
Microstructural geometrical parameters



Tension



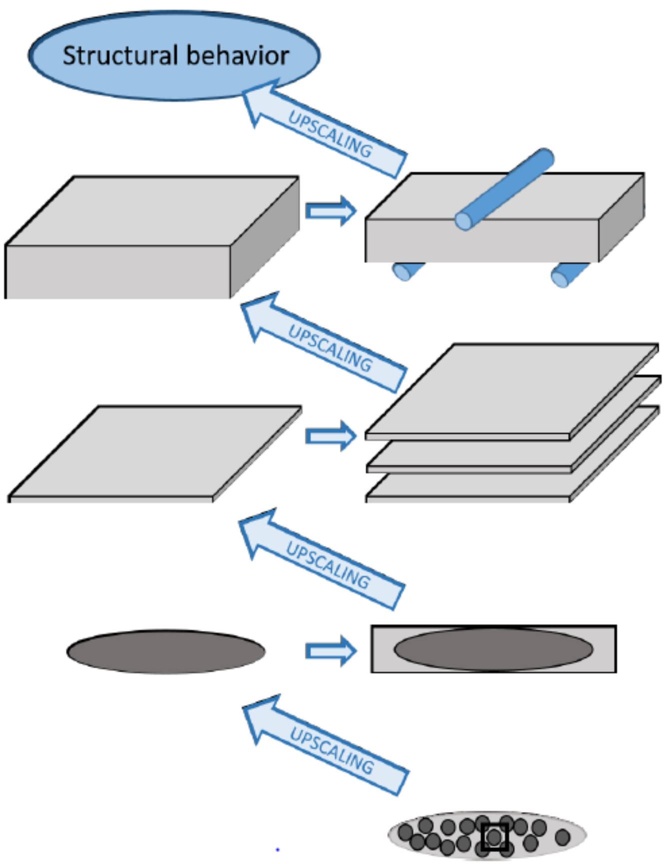
Tension - Modulus

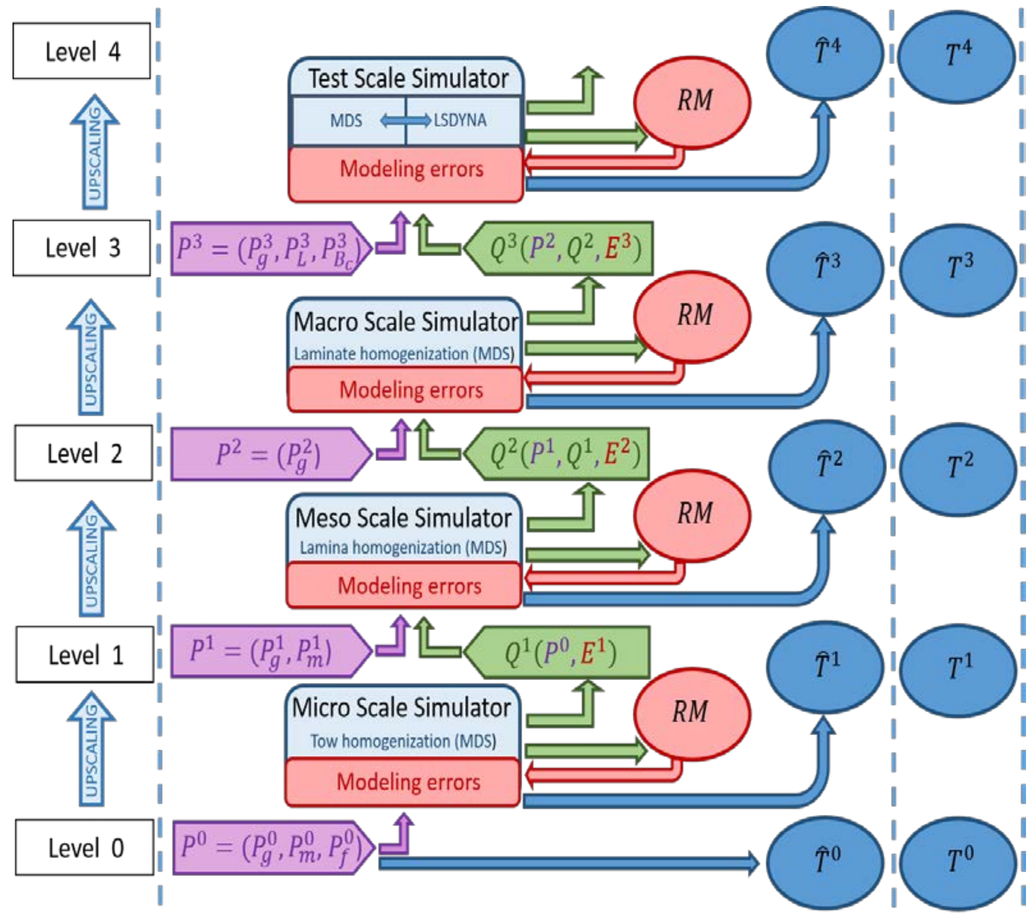


3-Point bend test 0 deg

Stochastic Structural Simulation

Framework





Responses to Previous Year Reviewers' Comments

This project was not presented at the 2015 Annual Merit Review.

Partners/Collaborators

General Motors - Prime	Overall project management, execution, baseline performance evaluation, material data generation for manufacturing and structural simulations, assembly of the CF automotive assembly, testing and validation. material database creation for manufacturing and structural simulation, integrate the manufacturing and structural models, develop cost models, demonstrate the technology development.
Continental Structural Plastics (CSP)	Material supplier, molder - coupons, plaques and components, develop design for manufacturing guidelines, input for cost models.
ESI Group, NA	Manufacturing simulation models for the manufacturing processes chosen in the project.
Altair	Multi-scale simulation models for the structural performance in the LS-DYNA, ABAQUS and Radioss framework.
University of Southern California	Develop stochastic drivers that work for manufacturing and structural performance simulations. Able to utilize the previous work done on a DOE supported work on uncertainty quantification (SciDAC institute).

Remaining Challenges and Barriers

- Predict and validate the stochastic manufacturing process simulations with experiments (15% of experimental results).
- Predict and validate the stochastic performance simulations with crashworthiness experiments (15% of experimental results).
- Accurately map the manufacturing outcome from manufacturing simulations into structural simulations

Proposed Future Work

FY 2016

- Complete data collection by conducting experiments to validate manufacturing and structural performance simulations tools.

- Complete the stochastic manufacturing simulation tool for following manufacturing processes
  - RTM, C-RTM, HP-RTM and prepreg compression molding

- Complete the stochastic performance simulation tool for three material systems friendly to high volume manufacturing.
  - NCF, Woven and Chopped material systems

FY 2017

- Integrate the manufacturing simulation tool with the structural performance simulations tool
- Design and optimize the carbon fiber reference automotive assembly using the integrated simulation tool.

Summary

- A framework for integrated manufacturing and structural performance simulation tool was developed and continually refined.
- Baseline performance requirements for the design of future carbon fiber automotive assembly were completed.
- Experiments were devised to generate data to validate manufacturing and structural performance simulation tools.
- Currently completing the validation of the stochastic manufacturing and structural performance simulation tool.

Technical Back-Up Slides

Governing Equations in Injection, Curing and Warpage

Filling – Stage – Coupled flow, heat and cure

Darcy's equation – Fluid Flow $\nabla \cdot (-\frac{K}{\mu}\overrightarrow{\nabla P}) = 0$

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

Curing Kinetics $\frac{d\alpha}{dt} = (A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m) \cdot (B - \alpha)^n$

Curing – Stage – Coupled heat and cure

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

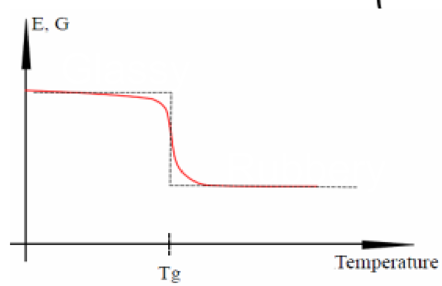
Curing Kinetics $\frac{d\alpha}{dt} = (A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m) \cdot (B - \alpha)^n$

Distortion- Stage (Thermo- Chemical Mechanical Analysis)

$$\sigma_{ij}(t) = \int_0^t C_{ijkl}\big(\xi(t) - \xi(\tau)\big) \frac{\partial\left(\epsilon_{kl} - \epsilon_{kl}^E\right)}{\partial \tau} d\tau \qquad C_{ijkl}(t) = \begin{cases} 0 & , X < X_{gel} \\ C_{ijkl}^{\infty} + \sum_{p=1}^{P} C_{ijkl}^{p} \cdot \left(e^{-t/\rho_{ijkl}^{p}}\right), X \geq X_{gel} & , no\ sum\ on\ i, j, k, \end{cases}$$

Di Benedetto function → T_g

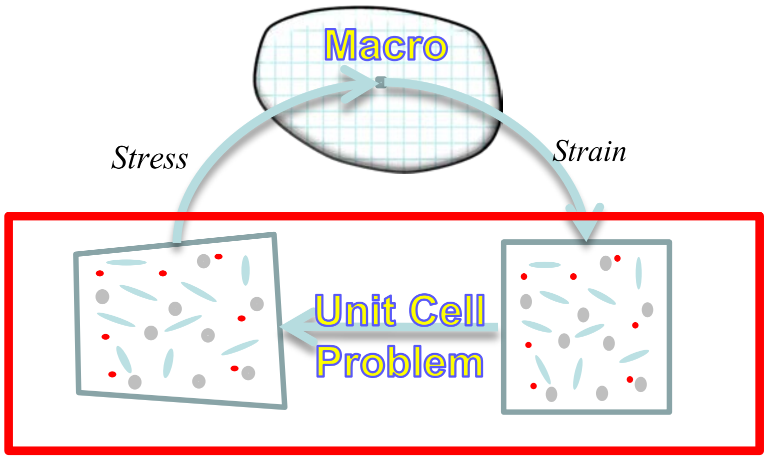
$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda X}{1 - (1 - \lambda)X}$$



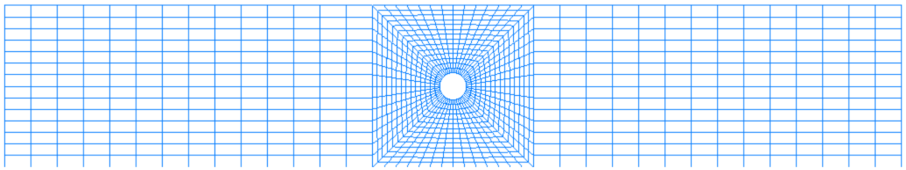
Multiscale Designer Capabilities

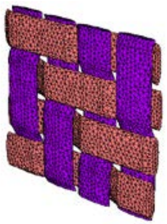
1. Parametric RVE definition
   1) Geometric scripts
   2) User-defined parametric RVE
   3) Integration with experimental data

2. Computational Efficiency: **Speed comparable to single scale model**



3. Size Effect & Softening after Damage





Challenges:

(1) Unit cell size comparable to the hole size and much bigger than macro-element size

(2) Strain softening due to damage

In attempt to account for size effect and softening due to damage

Remedies:

(1)Rescaling of damage models and

(2)Staggered nonlocal multiscale approach

END