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

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General Motors

2020 Annual Merit Review

June 3, 2020

Project ID: MAT117

Overview

Timeline

- Project Start Date: May 1, 2015
- Project End Date: December 18, 2019
- Percent Complete: 100 %

Budget

- Total project funding
  - DOE Share: $6,000,00
  - Contractor Share: $2,571,253
- Funding for FY19 :
  - DOE share: $1,589,333
  - Contractor share: $681,143
- Funding for FY20:
  - DOE Share: $0
  - Contractor Share: $319,861

Barriers and Technical Targets

Barriers addressed*

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.

*2017 U.S. DRIVE Roadmap Report, section 4

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) composite structures.
  - Reduce the cost of manufacturing CF reinforced automotive components by eliminating trial and error through improved manufacturing simulations.
  - Design, optimize and validate a CF automotive structure in a virtual design space through improved performance modeling.
  - Reduce the lead time and costs to design and implement large scale structural automotive composites.
  - Enable the usage of CF composites for significant light-weighting of automobiles and thus improve fuel economy, 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 for body and **$4.27** for chassis areas 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 for body and 25% for chassis)** compared to a current steel design.

Relevance

Steps in implementing CF in Automobiles

Current

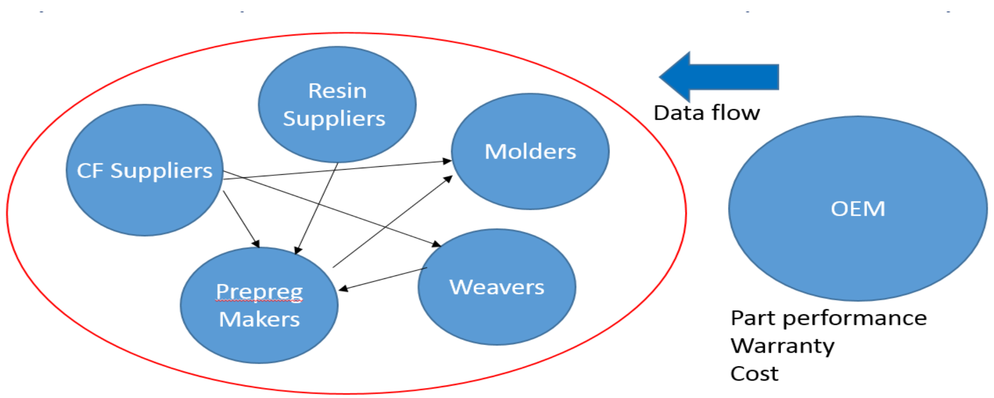
- Design.
- Selection of manufacturing process.
- Manufacturing feasibility.
- Prototype build and learn.
- Modify design and manufacturing process, if needed.
- Improve prototype build and make parts.
- Extrapolate to high volume manufacturing.
- Build the part, iterate to get good quality.
- Evaluate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

Future

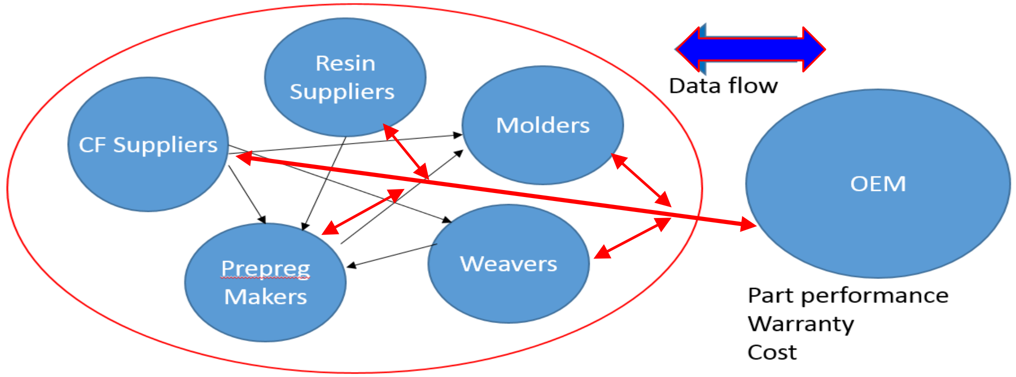
- Design.
- Virtual manufacturing simulation and improve the design for optimizing the cost.
- Include manufacturing outcome in performance simulation and further optimize the design to meet the requirements.
- Build tools, manufacture parts and check the performance

Workflow between OEM and Suppliers

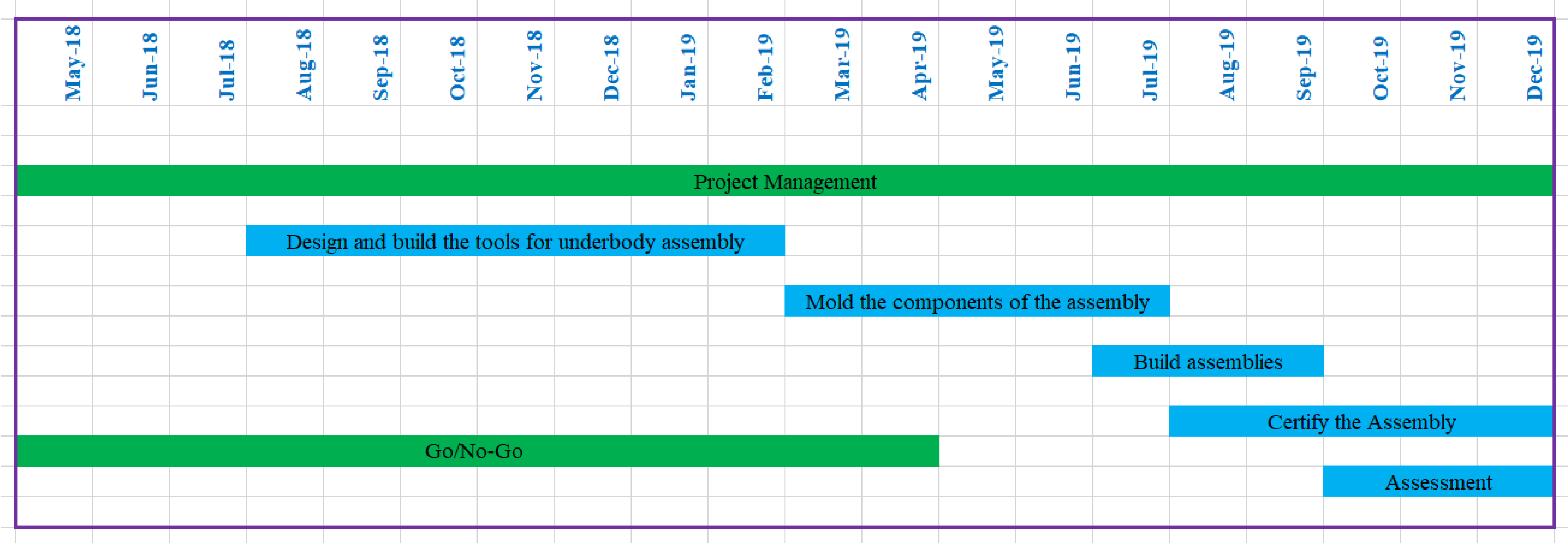
Current



Future



Milestones



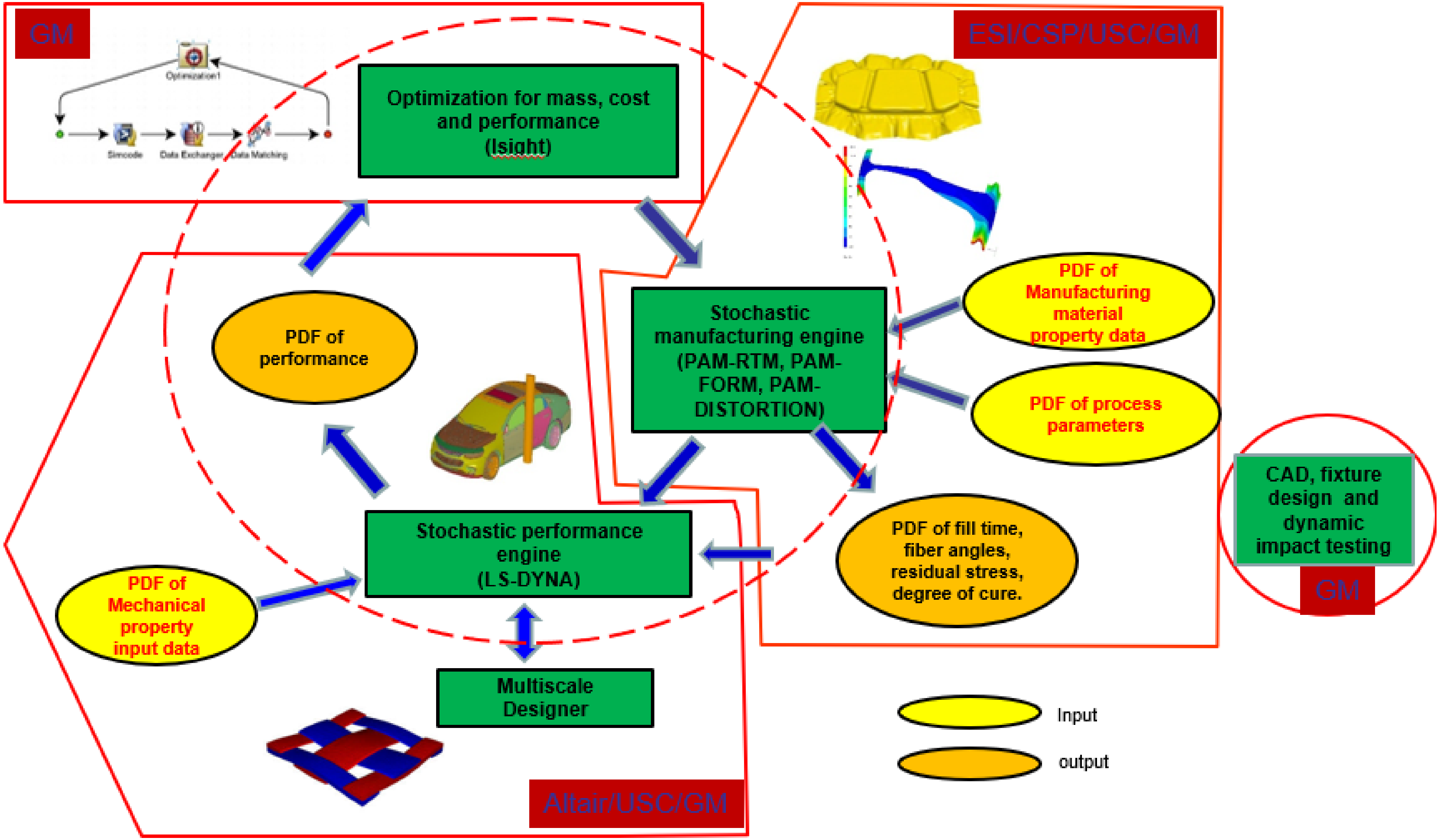
All milestones for year 2019 are complete.
Go/No-Go decision was also complete.
Project completed as of December 2019 and final project report was submitted

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, a Tier 1 composite system supplier and molder, software simulation companies in the areas of composite manufacturing and performance prediction, and a DOE funded SciDAC institute for uncertainty quantification.
- **Composite System Supplier**: Responsible for selecting materials and manufacturing processes for high volume manufacturing, providing plaques and coupons for generating the data required for model calibration and validation.
- **Software Companies:** Responsible for the development of predictive tools for manufacturing and structural performance.
- **Stochastic Modeling Research Group:** Responsible for developing stochastic models for both manufacturing and structural performance.
- **OEM:** Responsible for developing and conducting experiments for model confirmation, integrating the manufacturing and structural performance tools, demonstrating the technology by design, optimizing, building and testing a carbon fiber automotive assembly as well as validating the developed models by comparing the predictions with experimental results.

Approach/Strategy

Developed a process flow of tool development



Accomplishments

FY 19 Accomplishments

Fabricate the components

- Fabricated floor, reinforcement, rocker outer, rocker inner and energy absorber components for the underbody assembly.

Manufacturing simulation tool development and validation

- Validation of manufacturing models for high-pressure resin transfer molding of floor and reinforcement was complete.

Assembly of the components

- A total of 20 assemblies were manufactured.

Crash testing of the assembly

- A total of 14 assemblies were tested

Structural simulation tool development and validation

- Validation of structural models for side pole impact was complete.

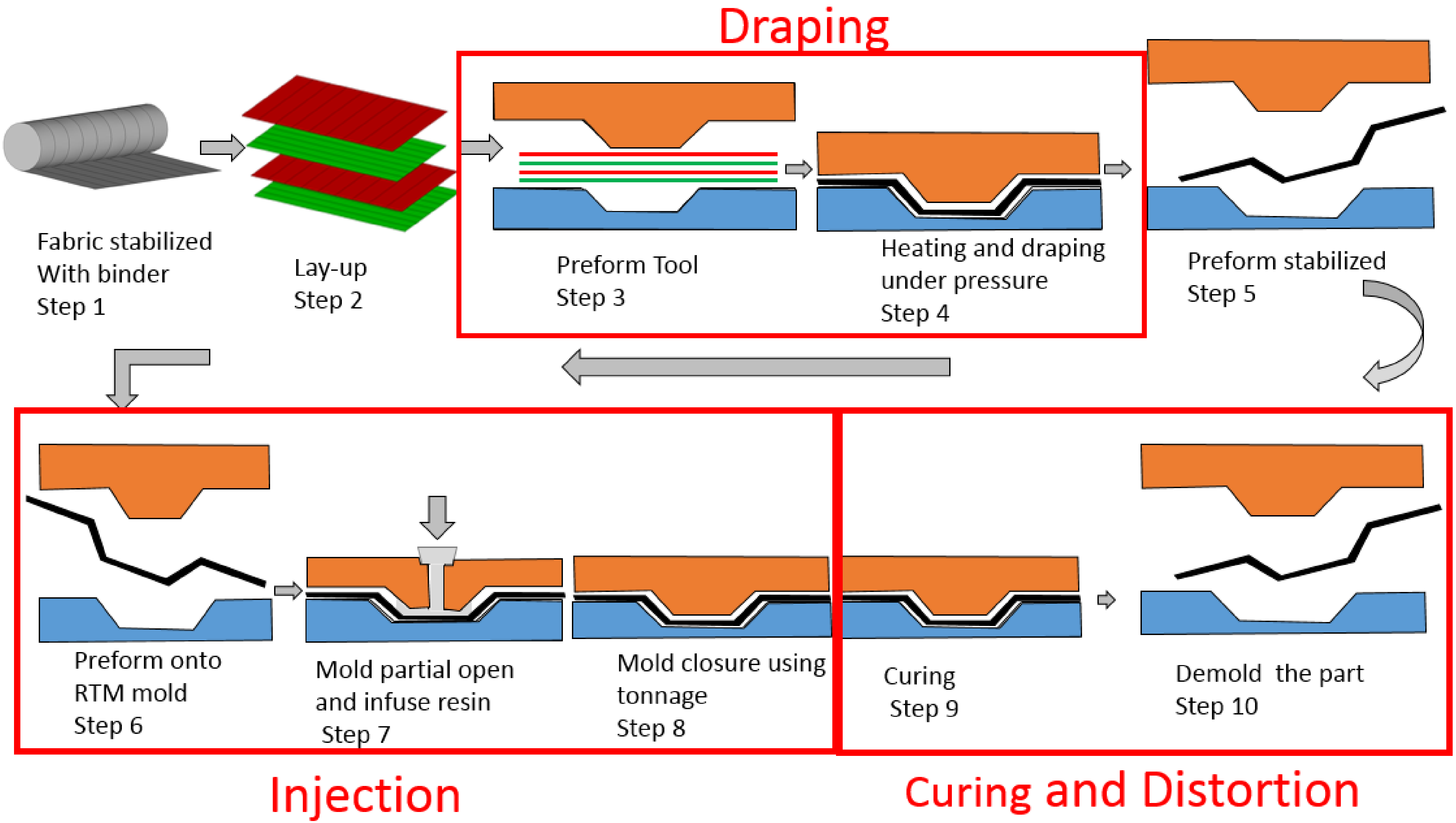
Patents

- A total of 10 patents submitted to U.S. Government Patent office.
- A total of 28 publications were prepared

Facilities

- GM commissioned a HP-RTM system to facilitate the molding for the project. Reinforcement component was molded at GM.
- CSP moved their HP-RTM equipment from France to CSP HQ in MI, USA. Floor, rocker outer and rocker inner components of the assembly were molded at the CSP facility.

Manufacturing Process



Current Project - Technology Impact Areas

Materials

- Low cost NCF
- Tow size effects (different numbers of fibers)
- Use of long fiber thermoplastic composite for energy absorption
- Stochastics at the micro-scale

Process

- Draping
- HP-RTM/C-RTM, process monitoring, and optimization
- Fast curing resins

Structure

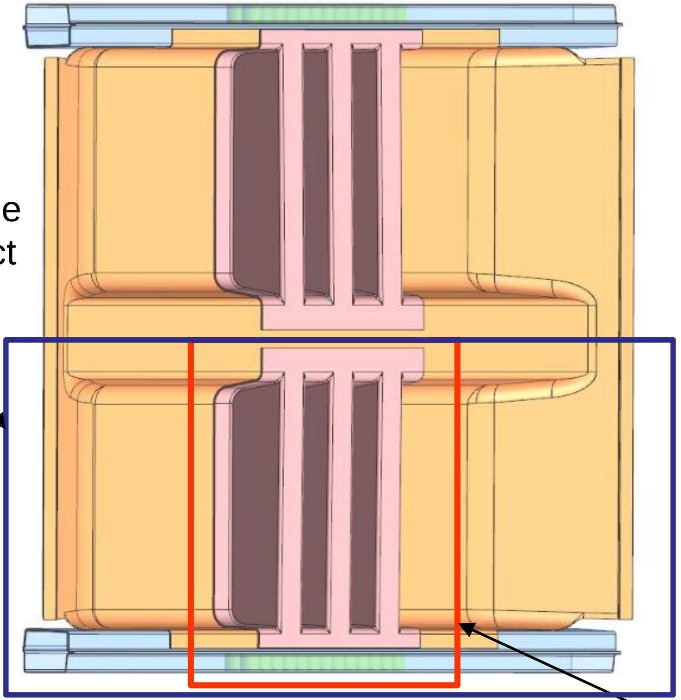
- Multi-scale
- Manufacturing effects
- Nonlinear plasticity

Performance

- Integrated performance
- Stochastic performance
- Non-orthogonal weaves
- Crashworthiness

Demonstration/Validation of Computational Tools

Built
For the
project



- Significant parts consolidation - more than 60 steel parts to 9 composite parts
- Carbon fiber design is 30% lighter than steel
- Further optimization is expected to improve the weight savings to ~ 40%

Light Weight Underbody
Ultra High Strength
Steel Assembly

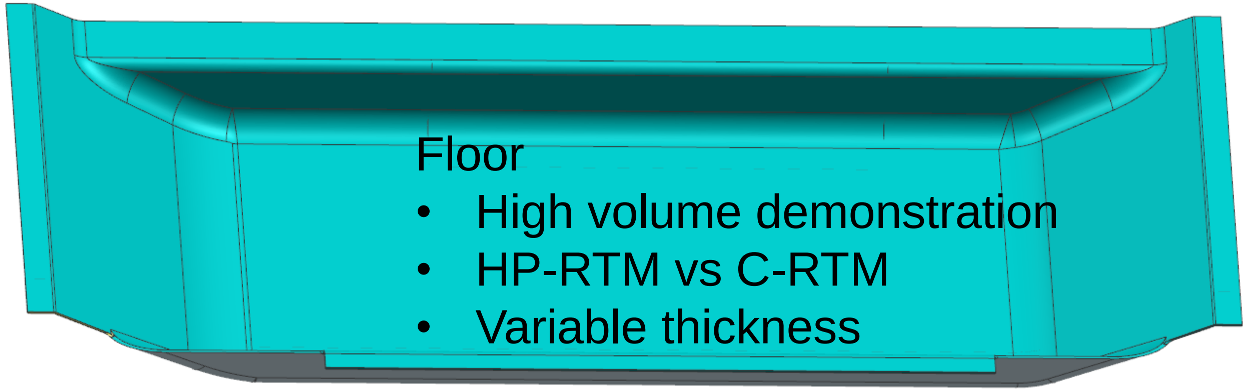
Replacement
Carbon Fiber
Assembly

Portion of the assembly built for the prototype evaluation

Objectives:

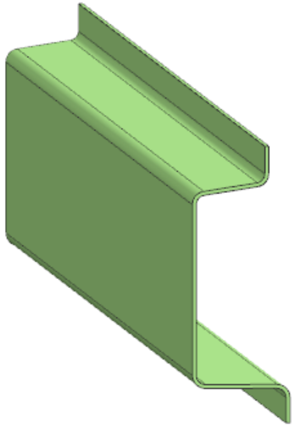
a) Demonstrate the HP-RTM technology for high volume manufacturing
b) Compare the side pole impact performance of carbon fiber with baseline steel by testing
c) Evaluate the weight savings and cost increase per pound saved

Carbon Fiber Parts – Underbody Assembly

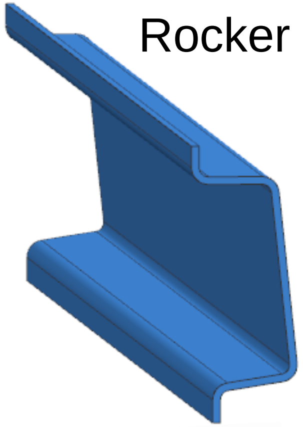


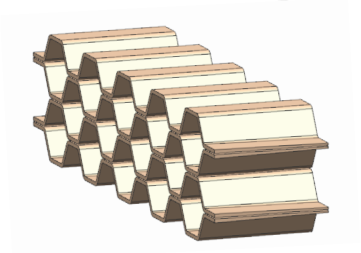
Floor
- High volume demonstration
- HP-RTM vs C-RTM
- Variable thickness

Rocker outer

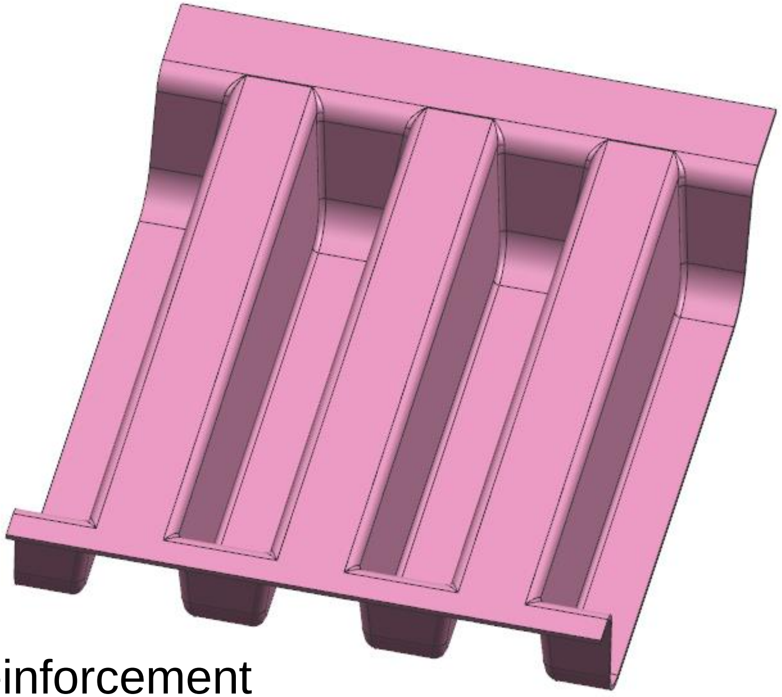


Rocker Inner





Thermoplastic
Energy absorber



Reinforcement
- Draping challenge due to complex geometry
- Slits for manufacturing effect the performance

GM HP-RTM System

- 1000T press
- Commercial injection system

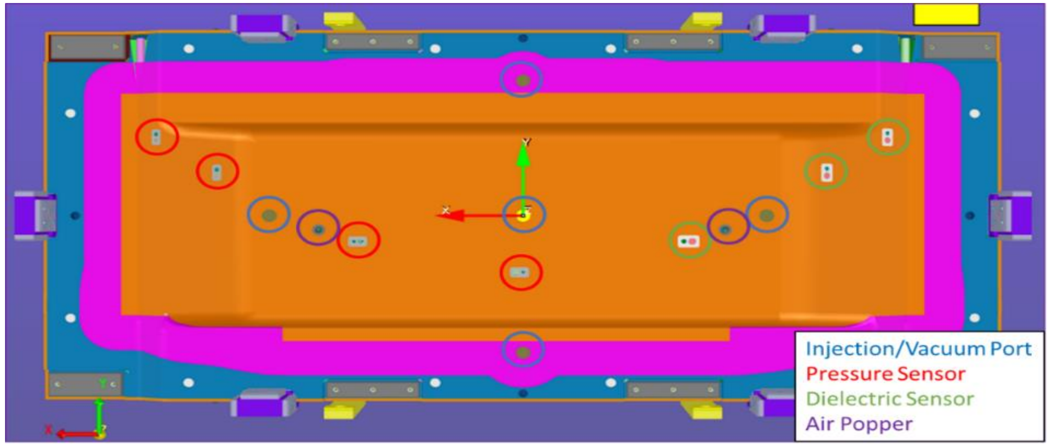
GM and CSP commissioned the HP-RTM systems in time to support the project

We believe this technology need to be explored to fullest potential to bring significant value to the composite industry

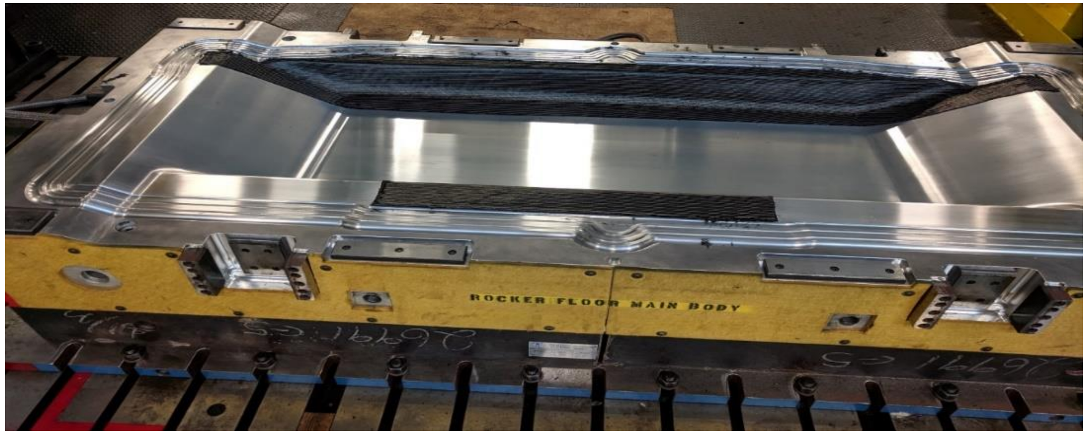
CSP HP-RTM System

- 4000T press
- Custom made injection unit

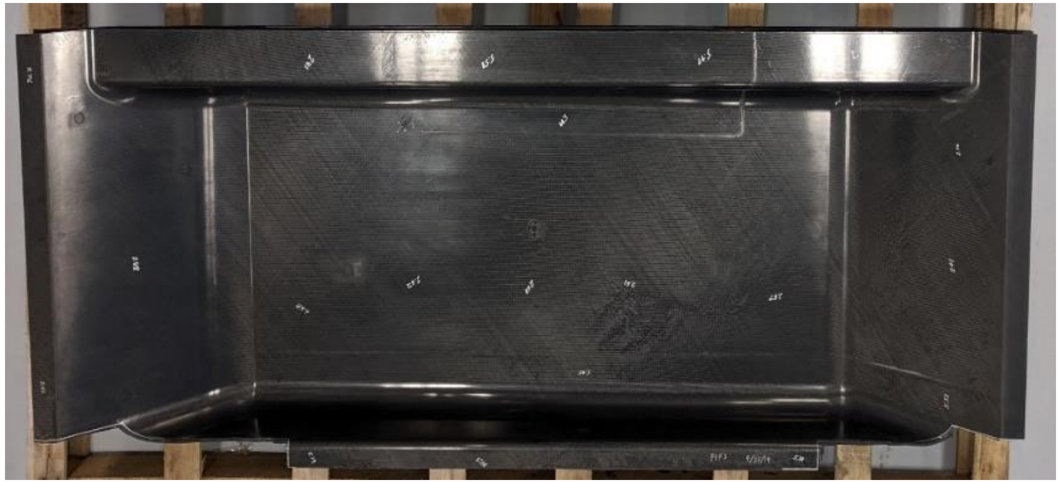
Manufacturing simulation tool development and validation



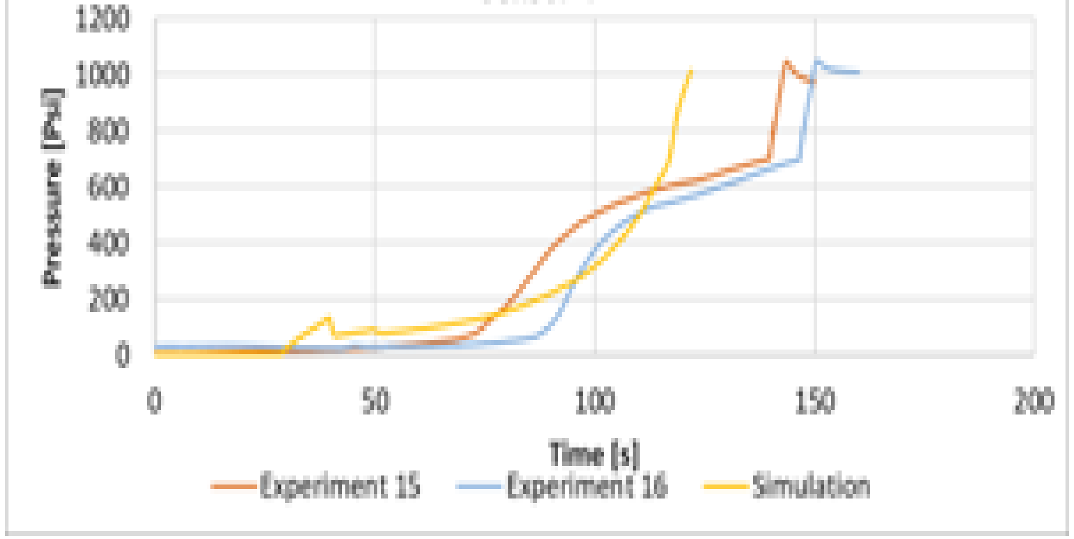
CAD of floor tool



Molded tool

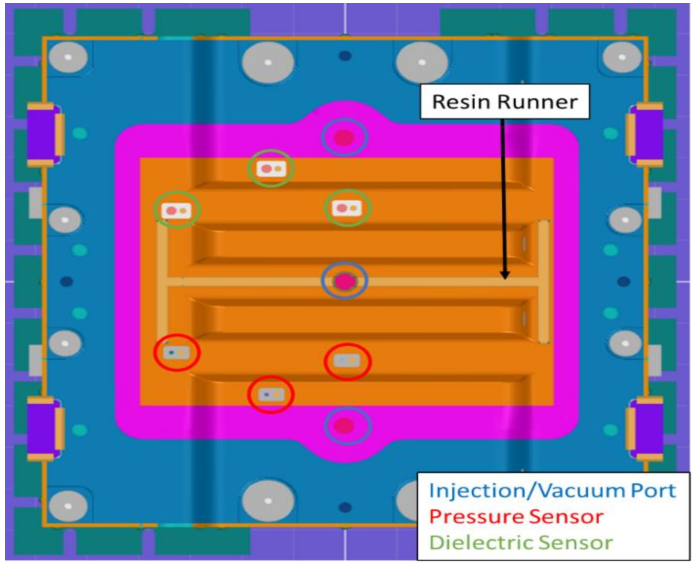


Floor part molded

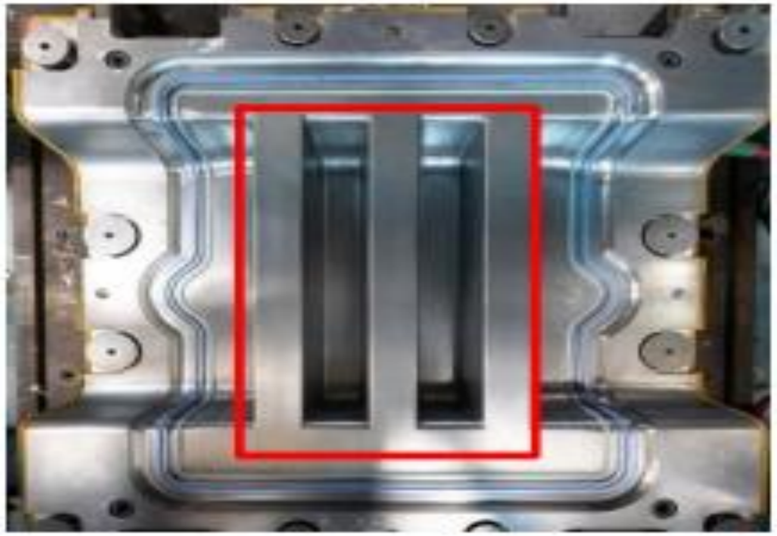


Comparison of pressure from simulation and experiment

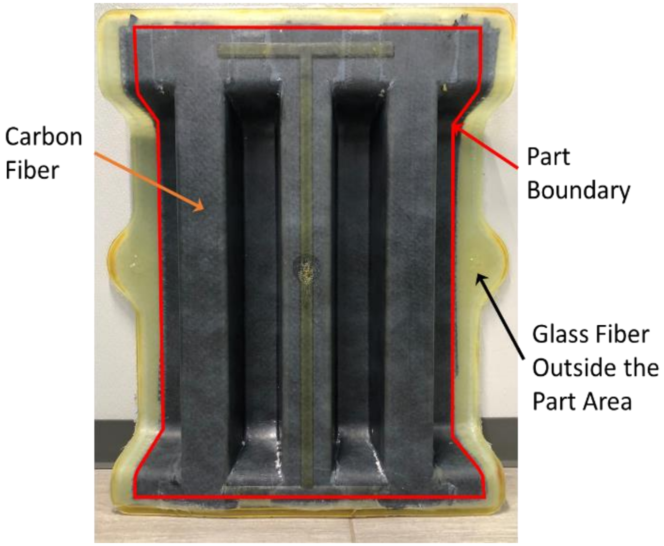
Manufacturing simulation tool development and validation



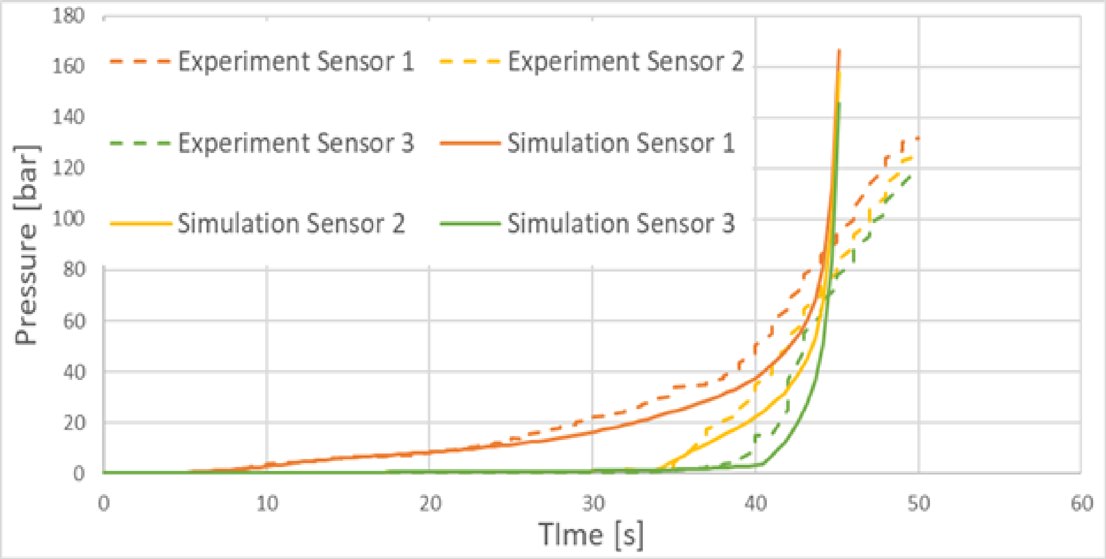
CAD of reinforcement tool



Reinforcement tool

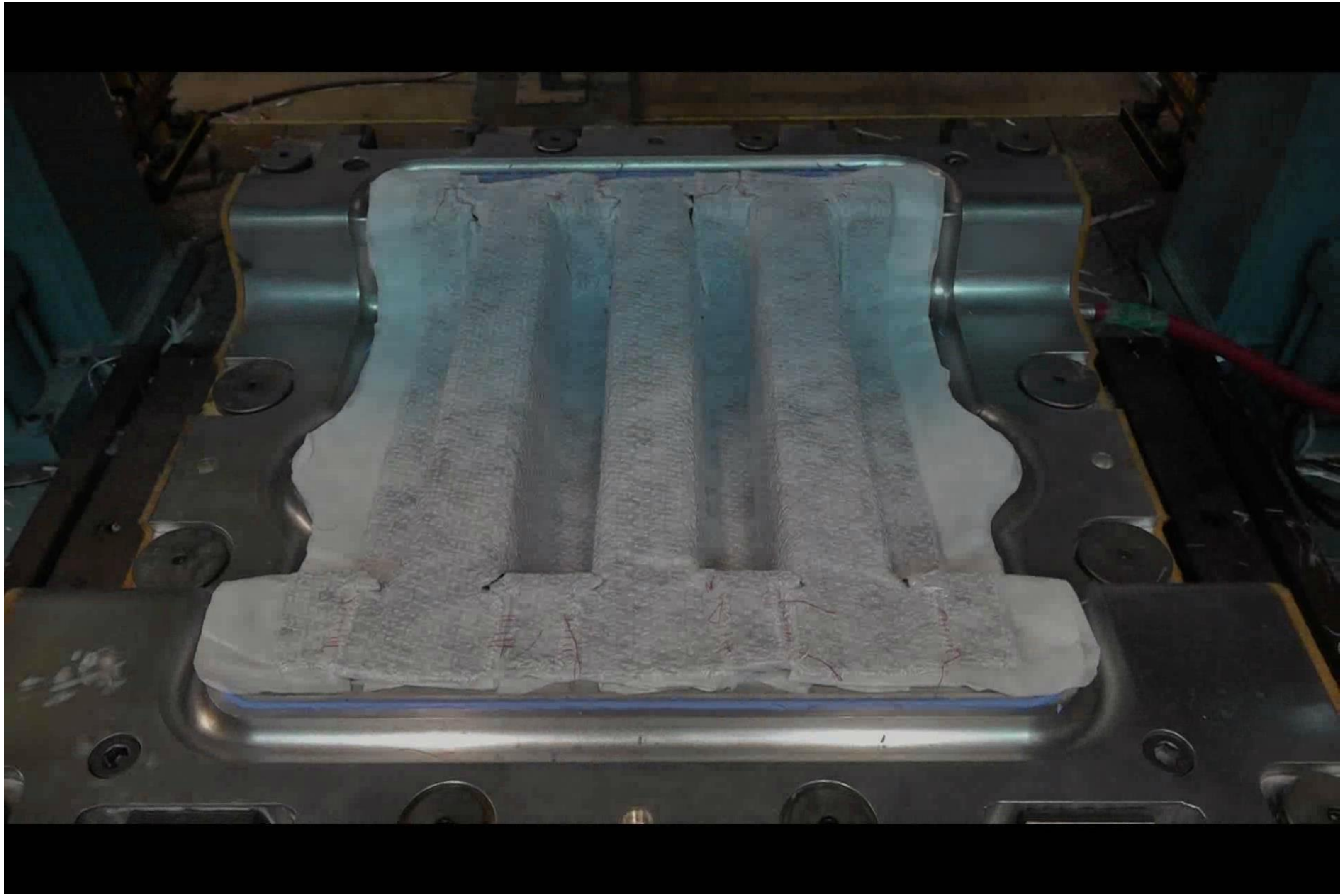


Reinforcement part molded



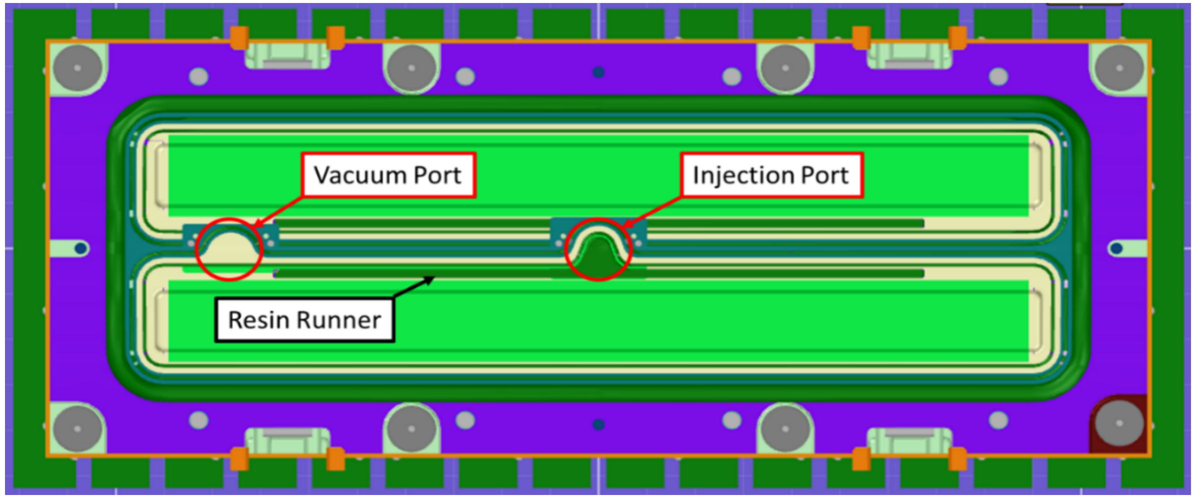
Comparison of pressure between simulation and experiment

Molding of Reinforcement Component



Video of 3 min. 10 sec. cycle time

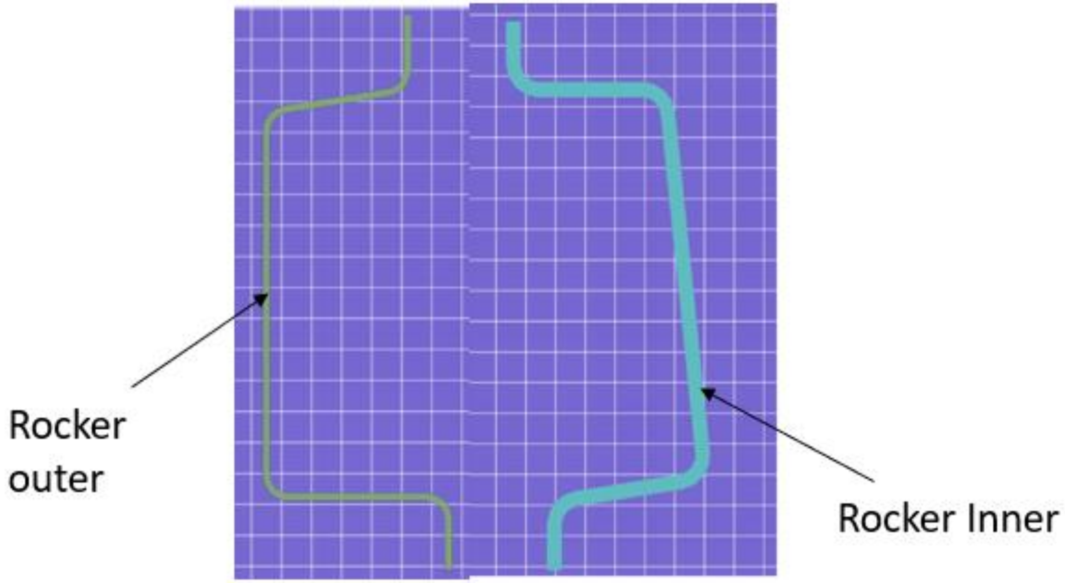
Manufacturing simulation tool development and validation



CAD of rocker outer and inner tool

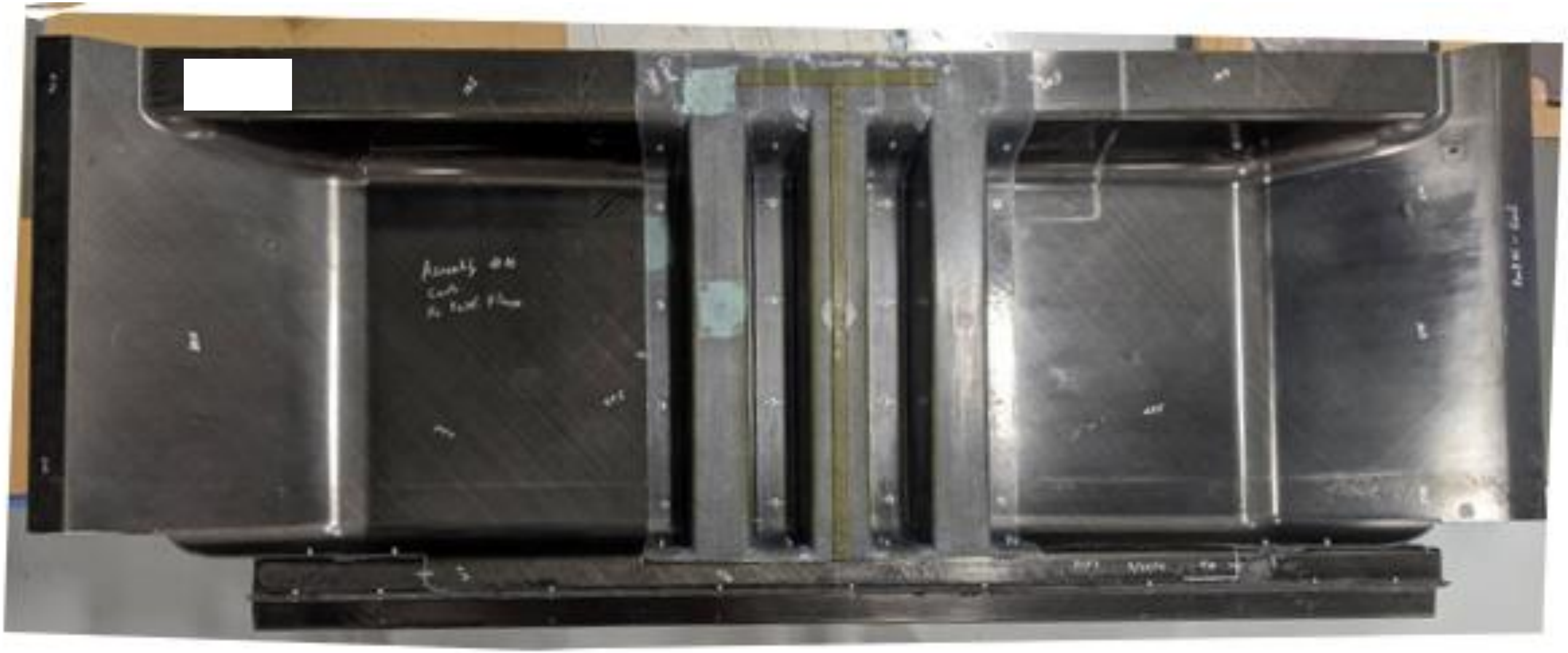
Rocker inner – 5 mm thick

Rocker outer – 2.5 mm thick



Rocker Assembly

Carbon Fiber Underbody Assembly



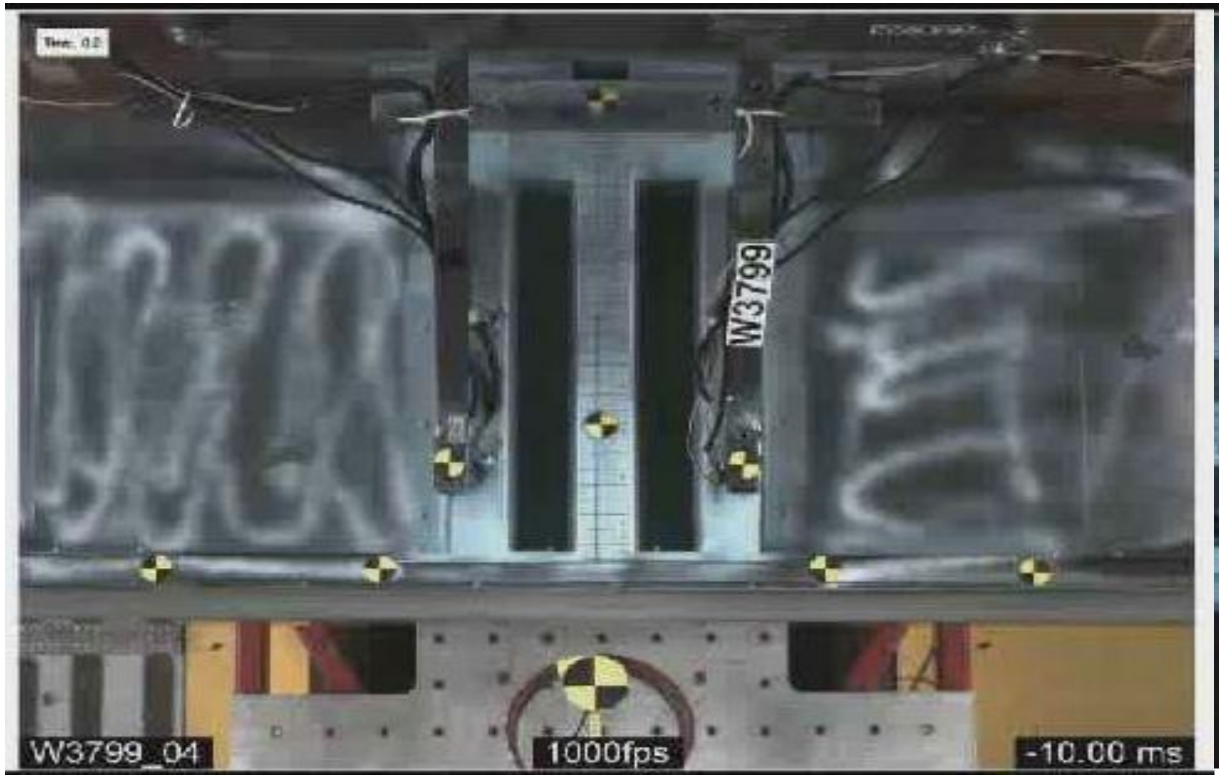
Adhesively bonded assembly

Mechanical fasteners at few locations to resist peeling

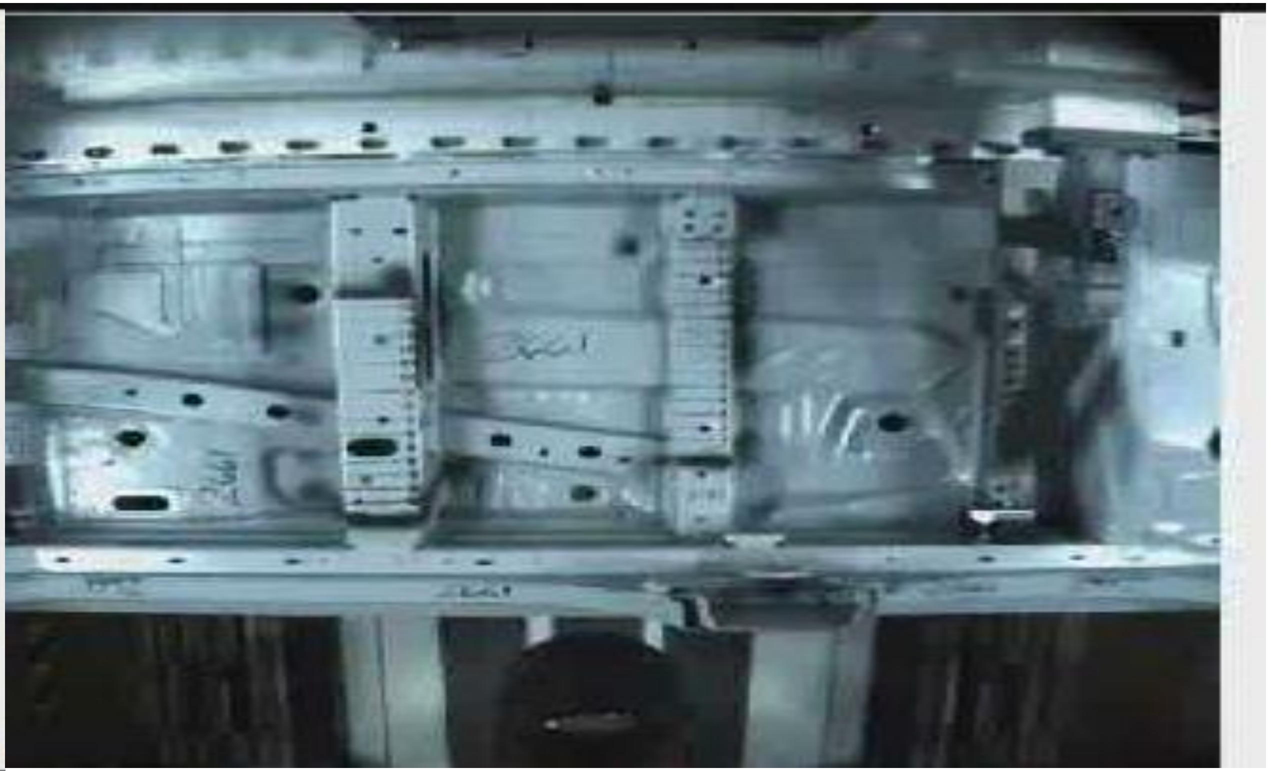
Crashworthiness Experiments

- Based on full vehicle simulations for the side pole impact, the underbody assembly of 2016 GM-Malibu absorbs around 27.3 KJ of energy during the side pole impact
- Baseline steel assembly was tested with 27.3 KJ of energy under side pole impact and recorded the intrusion.
- All-carbon fiber assemblies were tested with 28 KJ of energy under the side pole impact and compared the intrusion with the baseline steel assembly.

Underbody Assembly – Side Pole Impact

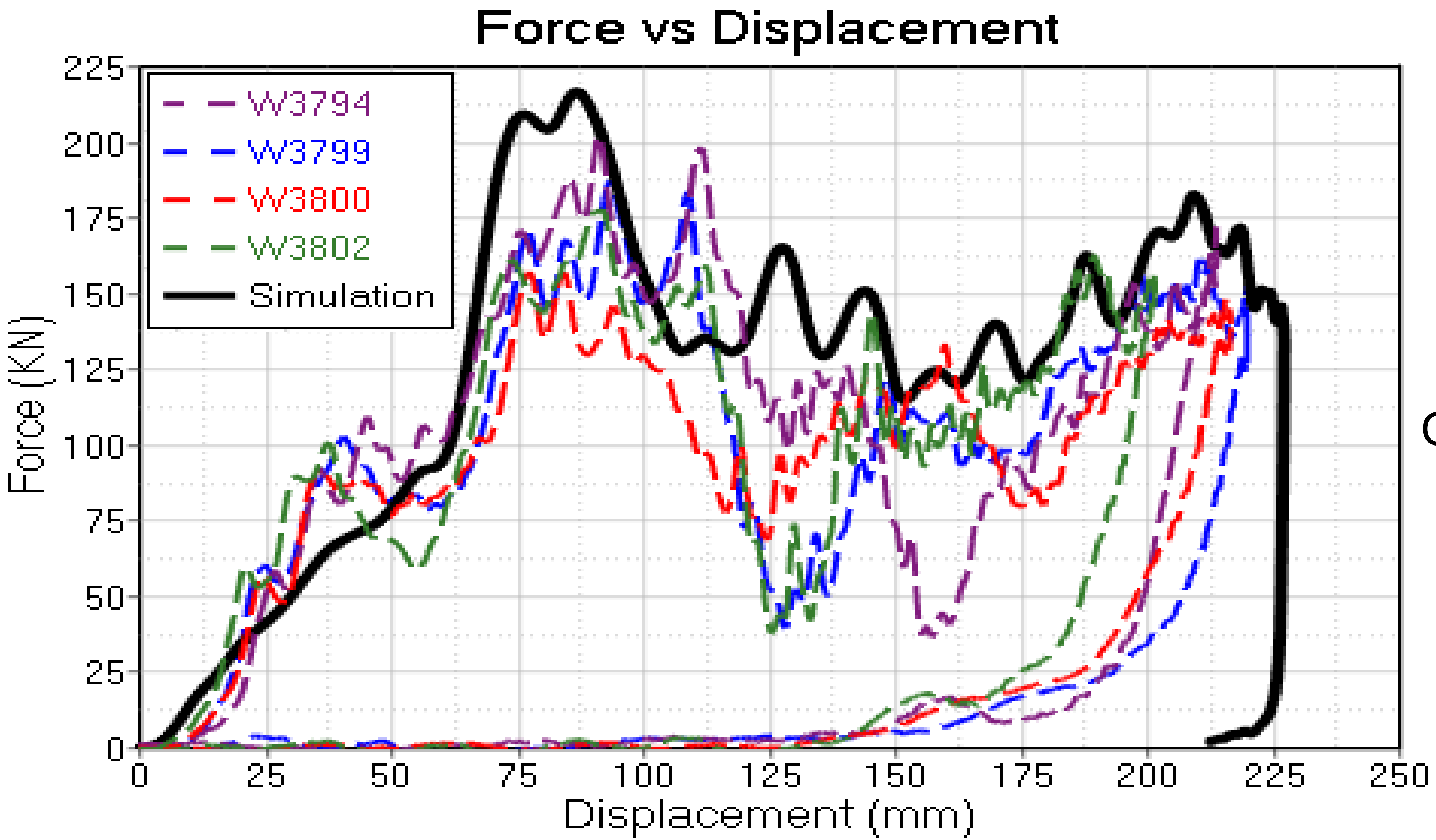


Carbon Fiber Design
(intrusion 115 mm)



High Strength Steel Design
(intrusion 221 mm)

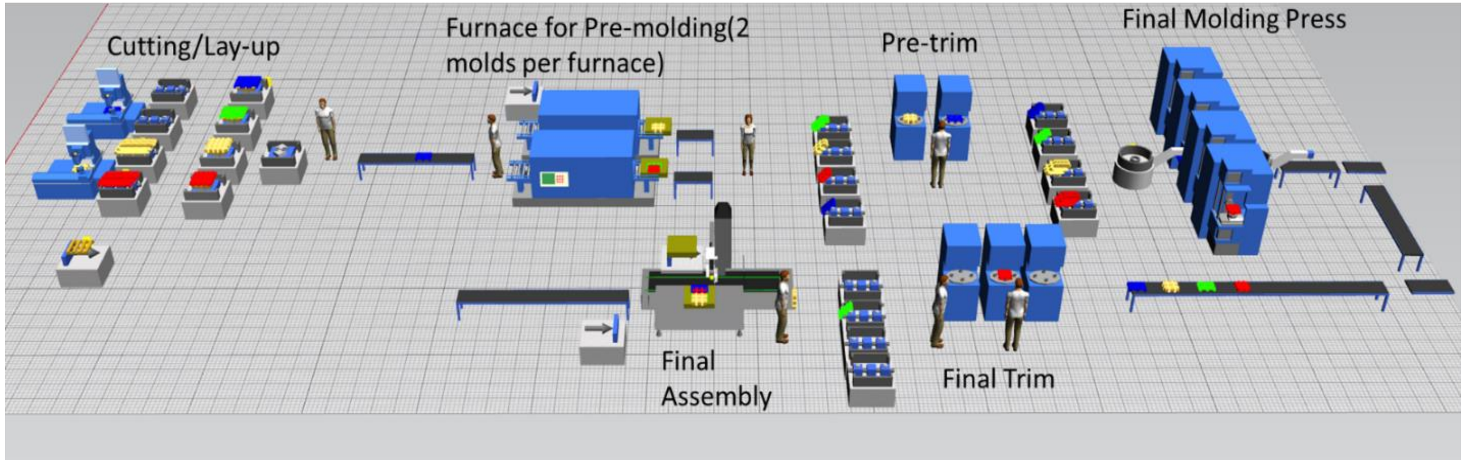
Carbon fiber design has intrusion close to half of the steel assembly!

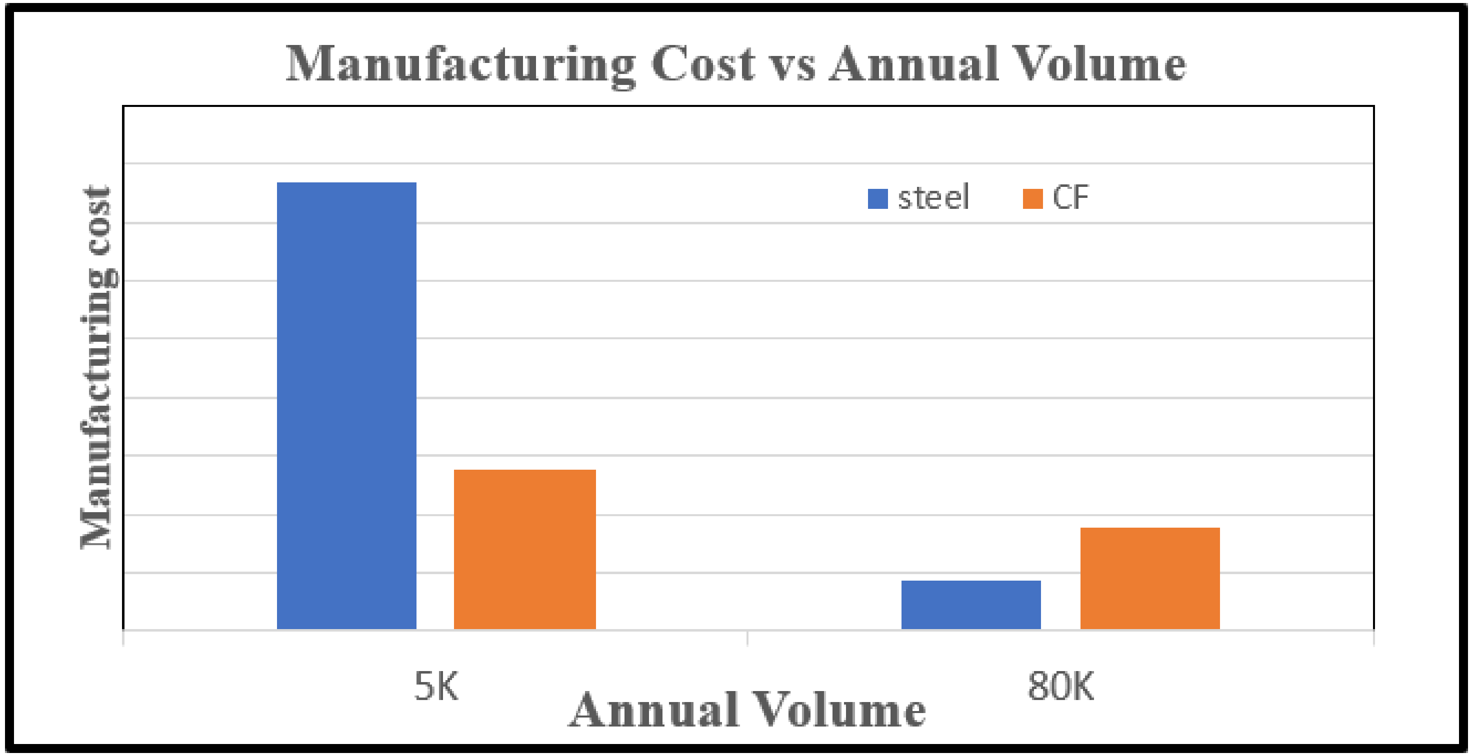


Good Correlation

Comparison of predicted load versus experimental load

Cost Models





- Cost models show that the cost increase per pound saved is ~$10 compared to DOE metric of $4.32.
- Some costs for the steel are not available
- More effective use of carbon fiber material is needed

Responses to Previous Year Reviewers' Comments

As the project was in the final year, no reviews were made.

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)	Technology 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

(Any proposed future work is subject to change based on funding levels)

- None

Proposed Future Research

- Development of hybrid fiber reinforcement preforms – combination of glass and carbon. Expensive carbon will be used in critical regions. Fiber placement to orient the fibers.
- Productionize the HP-RTM process with more demonstrations
- Multi-functional composites (self-health monitoring, actuators in the composite, etc.)

Summary

- Three large HP-RTM tools were built, and four components were fabricated to assemble an underbody assembly.

- The assembly was tested for side pole impact for the same energy as the baseline steel assembly.

- The carbon fiber energy assembly demonstrated exceptional performance with half the intrusion compared to the steel assembly.

- ICME tools were validated for both manufacturing and structural performance. Some improvements in manufacturing predictions were required to make the predictions more accurate.

Thank You!

Technical Back-Up Slides

Governing Equations in Injection, Curing and Warpage

Filling – Stage – Coupled flow, heat and cure

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

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

Curing – Stage – Coupled heat and cure

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

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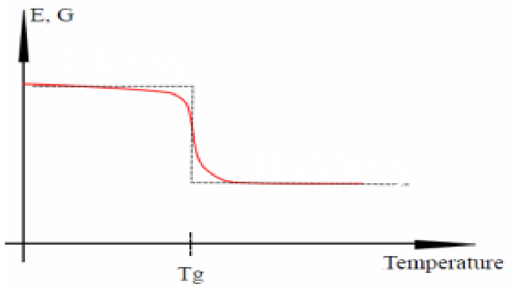
Distortion- Stage (Thermo- Chemical Mechanical Analysis)

$$\sigma_{ij}(t) = \int_0^t C_{ijkl}\big(\xi(t) - \xi(\tau)\big) \frac{\partial\left(\epsilon_{kl} - \epsilon_{kl}^E\right)}{\partial \tau} d\tau$$

$$C_{ijkl}(t) = \begin{cases} 0 & , X < X_{gel} \\ C_{ijkl}^{\infty} + \sum_{p=1}^{P} C_{ijkl}^{p} \cdot \left(e^{-t/\rho_{ijkl}^{P}}\right), X \geq X_{gel} & , no\ sum\ on\ i, j, k, l \end{cases}$$

Di Benedetto function → T_g

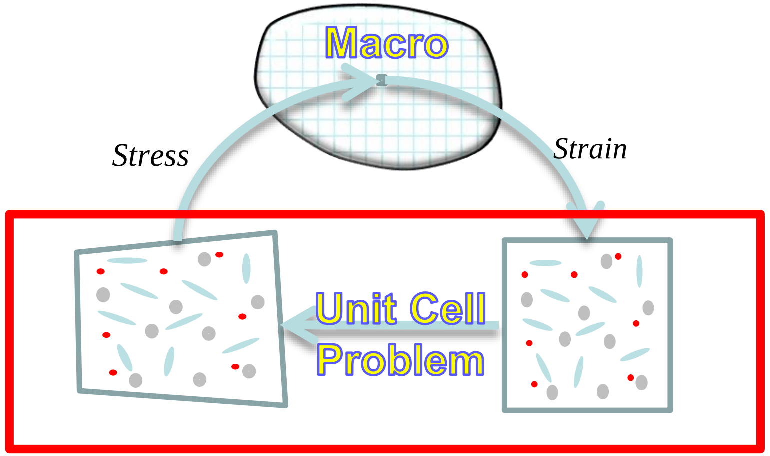
$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda X}{1 - (1 - \lambda)X}$$



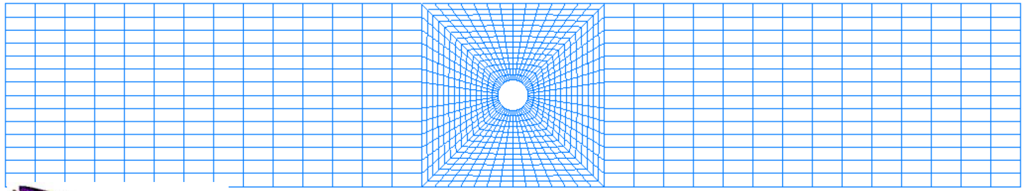
Multiscale Designer Capabilities

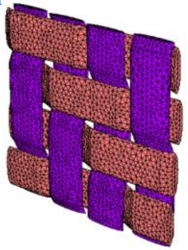
1. Parametric RVE definition
   1) Geometric scripts
   2) User-defined parametric RVE
   3) Integration with experimental data

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

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

Remedies:
(1) Rescaling of damage models and
(2) Staggered nonlocal multiscale approach