Integrated Computational Materials Engineering (ICME) Development of Carbon Fiber Composites for Lightweight Vehicles

Dr. Xuming Su (PI)
Dr. David Wagner (Co-PI)

Ford Motor Company
June 19, 2018

Project ID: MAT101

Overview

Timeline

- Project start date: Oct. 1, 2014
- Project end date: Dec. 30, 2018
- Percent complete: 72% Complete (based on budget at end of FY17)

Budget

- Total project funding
  - DOE share: $6,000,000
  - Contractor share: $2,580,000

  Funding in FY 2014: $34,506

  Funding for FY 2015: $594,341

  Funding for FY 2016: $1,616,967

  Funding for FY 2017: $2,073,638

  Remaining Funding for FY 2018: $1,680,548

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

Barriers

- Predictive modeling tools
  - ICME models for Carbon Fiber Reinforced Polymer composites (CFRP)
  - Error of model predictions vs tests ≤15%
    - Manufacturing process models
    - Vehicle performance models
- Performance
  - Achieving ≥25% weight reduction
  - Meet packaging, safety and durability requirements of vehicle structure
- Cost
  - Cost increase ≤$4.27/lb of weight saved

Partners

- Ford Motor Company (Lead)
- Dow Chemical
- Northwestern University
- NIST/University of Maryland

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Relevance and Project Objective

- **Overall Objectives**
  1. Develop **predictive** Integrated Computational Materials Engineering (ICME) **modeling tools**
     - Simulate the manufacturing process effects on material properties
     - Predict part and assembly attributes (safety, durability, strength and NVH)
       - Material models based on material design and manufacturing processes
       - CAE analysis accounting for local material variations due to process influences
     - Error of model predictions vs experimental measurements ≤15%
  2. Design and optimize a carbon fiber front subframe for a five passenger sedan using ICME models developed (CAE only, no prototypes or vehicle tests)
     - **Meet packaging, NVH, safety and durability requirements**
     - Capable of achieving **≥ 25% weight reduction**
     - **Cost penalty ≤ $4.27 / lb of weight saved**
- **Impact / Relevance to DOE**
  - Speed up the application of CFRP in vehicle structures for lightweighting to address the DOE 2030 targets
  - Improve CAE prediction capability to achieve the most efficient design of lightweight, high quality CFRP vehicle structures at lowest cost

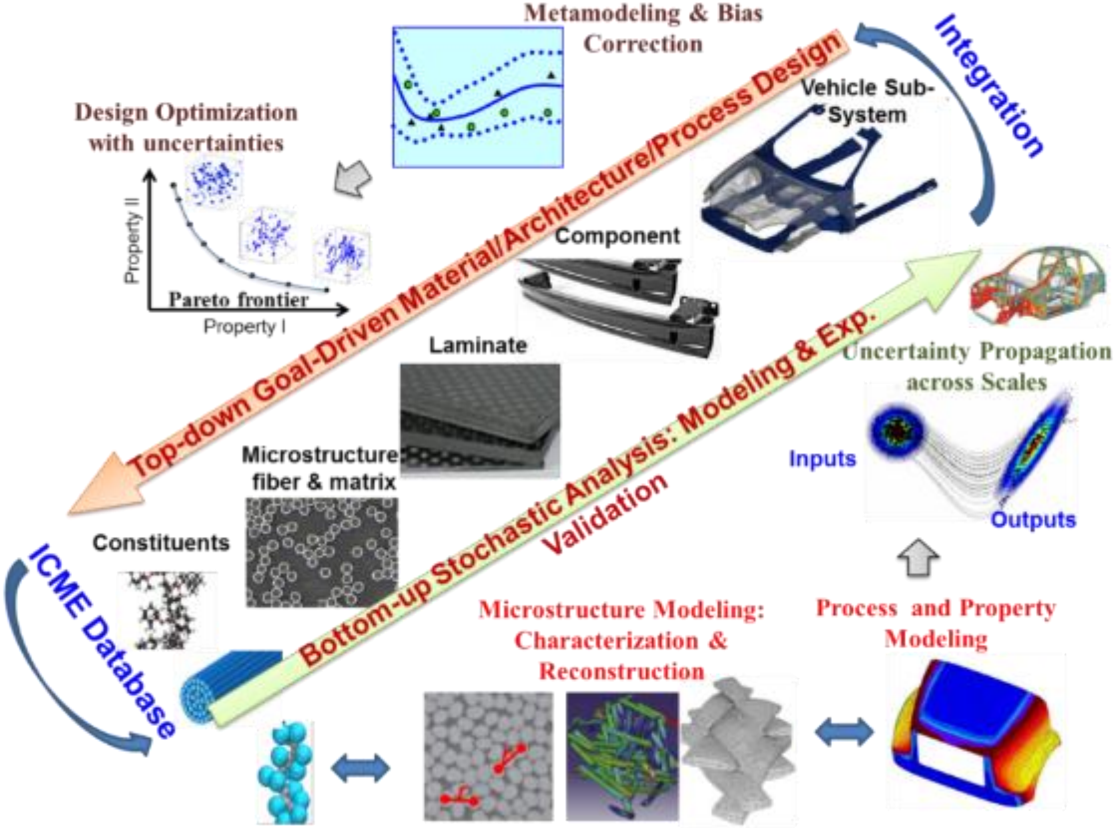
Milestones

<table>
<tr><th>Milestone</th><th>Date</th><th>Status</th><th>Type</th></tr>
<tr><td>ICME model integration completed and validated</td><td>6/30/2017</td><td>Completed</td><td>Technical</td></tr>
<tr><td>ICME model validation completed</td><td>9/30/2017</td><td>Completed</td><td>Technical</td></tr>
<tr><td>Model accuracies meet specified targets</td><td><s>9/30/2017</s>
12/31/2017</td><td>Completed</td><td>Technical</td></tr>
<tr><td rowspan="2">Integrated ICME model meets accuracy targets</td><td>12/31/2017</td><td>Completed
for Top Hat</td><td>Go/No Go</td></tr>
<tr><td>6/29/2018</td><td>On Track
for Subframe</td><td>Go/No Go</td></tr>
<tr><td>Subframe Design Concepts Developed</td><td>3/30/2018</td><td>Completed</td><td>Technical</td></tr>
<tr><td>ICME Model Reliability, Robustness and Efficiency Assessed</td><td>6/30/2018</td><td>On Track</td><td>Technical</td></tr>
<tr><td>Design Optimization Completed; Performance, Weight and Cost</td><td>9/30/2018</td><td>On Track</td><td>Technical</td></tr>
<tr><td>Complete project summary and reports</td><td>12/31/2018</td><td>On Track</td><td>Project End</td></tr>
</table>

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

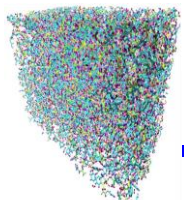
Approach / Strategy

- Develop predictive tools using Integrated Computational Material Engineering
  - Top-down goal-driven design & optimization
  - Bottom-up multi-physics, multi-scale modeling
  - Integration of models of materials, processes, structural performances, and cost
- Apply ICME tools to achieve the most efficient design of lightweight, high quality CFRP vehicle structure with low cost



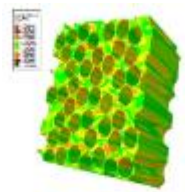
Approach: Budget Periods 1-3 Task Teams

Task 1
Material and Material Characterization



Task 2.1
Molecular Dynamic Analysis (MDA)

Task 2.2
Multiscale Modeling Representative Volume Element (RVE)



Task 2.6
Uncertainty Quantification and Propagation

Task 2.31 Forming Analysis (laminates)

Task 2.32 Molding Analysis (chopped fibers)

Task 2.4 Crash Analysis
Task 2.5 Fatigue Analysis

Task 3 ICME Model Integration and Validation

Material Design → **Preforming & Compression Molding Analysis (LS-DYNA, Moldflow)** → **Crash (LS-DYNA)** / **Durability (nCode)** / **Strength (ABAQUS)** / **NVH (NASTRAN)** → **Design Optimization (modeFRONTIER)**

Approach: Budget Periods 3-4 Task Teams

Task 3 ICME Model Integration and Validation

Task 3.2 Software Interface Development

Task 3.1 ICME Model Integration in Commercial Software

Task 3.3 Model Reliability, Robustness and Efficiency

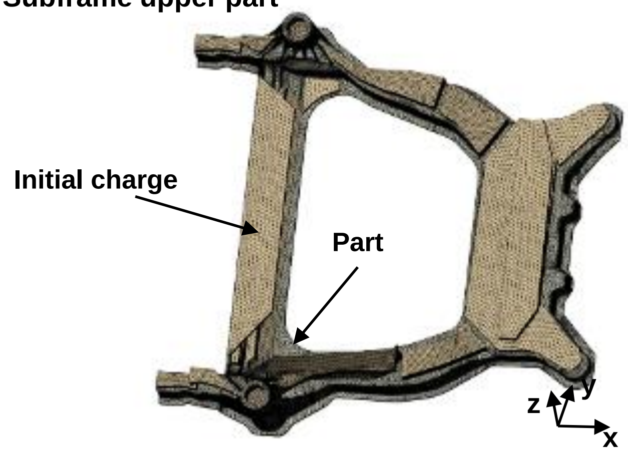
Task 3.4 Assembly-Level Testing and Model Validation

Task 4 ICME-Based Design and Optimization

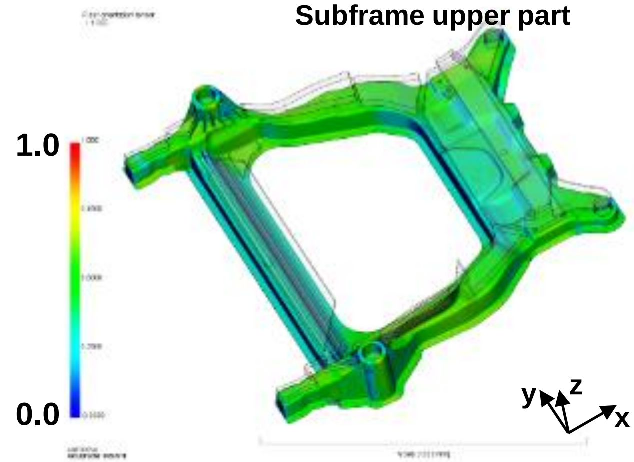
Accomplishments: Subframe Compression Molding

- Compression molding simulation is completed for Carbon Fiber SMC intensive subframe design
  - **Moldflow** model is high in computational cost due to complex part geometry
    - 6.5 million elements for subframe upper half model, ~90 hrs run time on Ford HPC

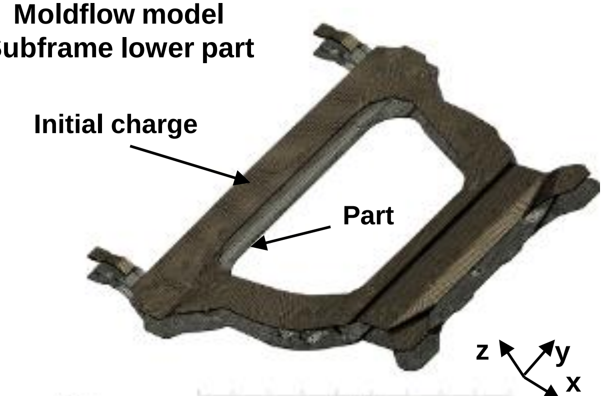
Moldflow model
Subframe upper part



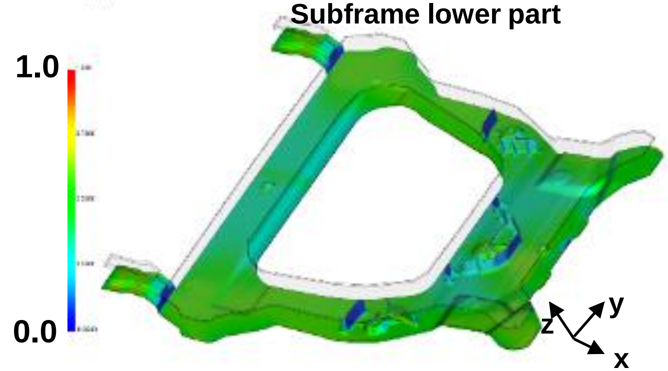
Fiber orientation component Axx
Subframe upper part



Moldflow model
Subframe lower part

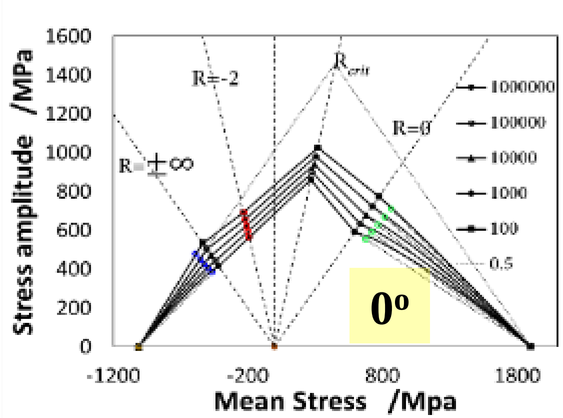


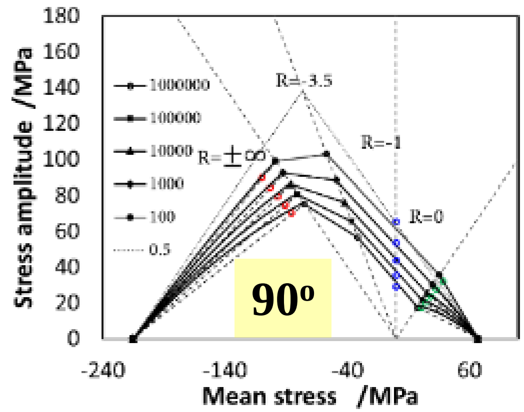
Fiber orientation component Axx –
Subframe lower part



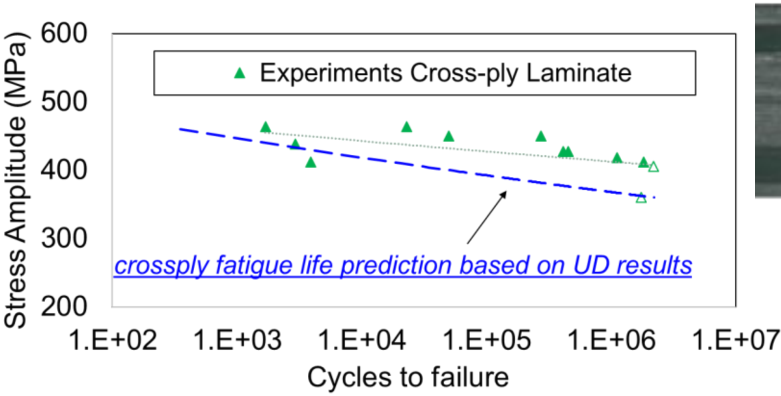
Accomplishments: Fatigue Testing & Modeling

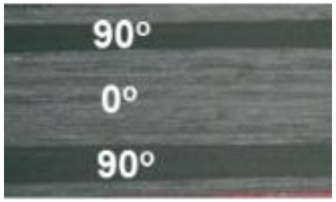
- Completed all the fatigue tests for **unidirectional laminates** at 0º and 90º to construct the constant fatigue life diagrams



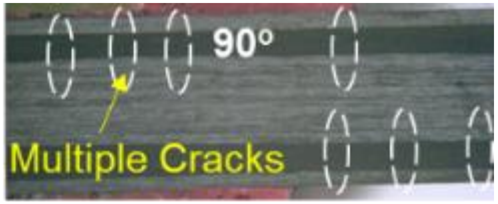


- Applied the constant fatigue life diagrams and the new composite fatigue prediction module in nCode to **predict** the fatigue strength of a cross ply $(0/90/90/0/0/0)_S$ laminate structure





Before loading



After 10 cycles

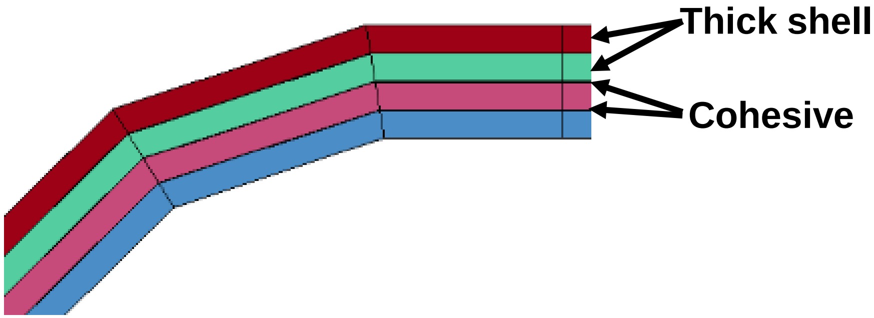
Final failure

At 2×10^6 cycles, the difference between the predicted (361 MPa) and the experimental (410 MPa) fatigue strength is within 15%

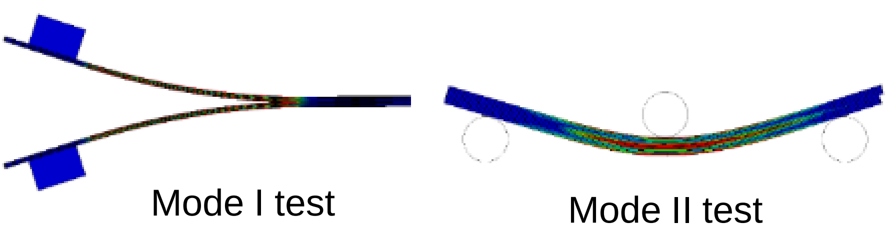
Accomplishments: Fracture and Energy Absorption

Development Highlight

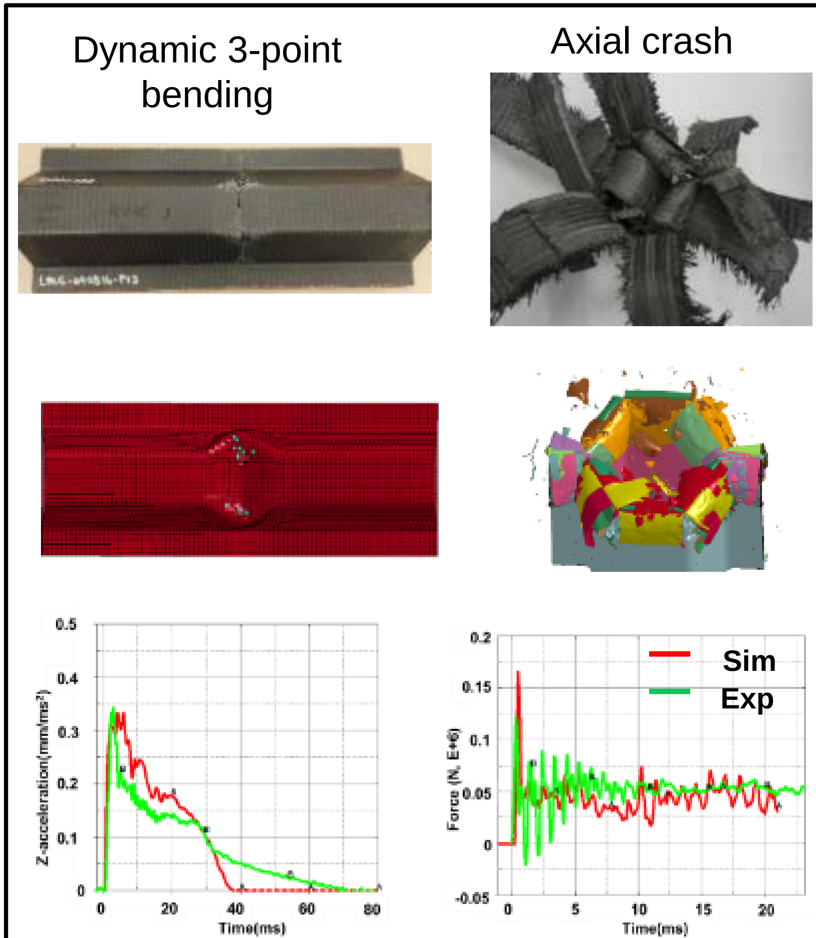
- Model setup: thick shell with cohesive elements



- MAT54 with Change-Change failure criterion in LS-DYNA for Intra-laminate failure
- Cohesive elements with strain rate effect for Inter-laminate failure; parameters calibrated from modeling of Mode I and Mode II fracture tests

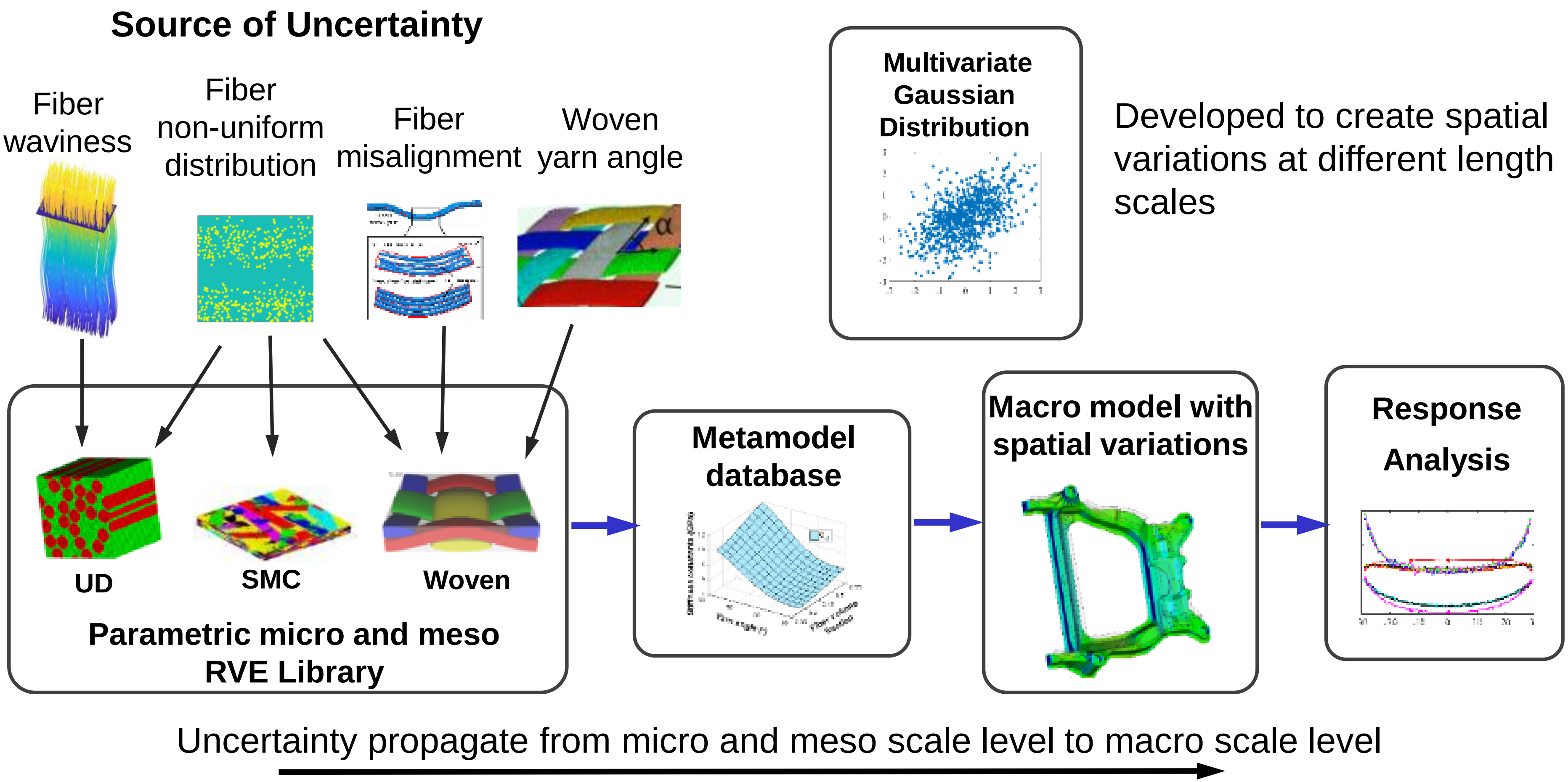


Crash of woven composite



Completed an accurate meso-scale approach for CF composite crash simulation to predict two different failure modes

Accomplishments: Uncertainty Quantification



- Completed a systematic approach to quantify the uncertain at different scale and the propagation across the length scales
- The full UQ package with user friendly interface will be completed in 09/2018

Accomplishments: Process Integration
ICME Workflow for CF Composite Design

Design Optimization Tool (modeFRONTIER)

Step 1: Build the Parametric Models

Step 2: Define design variables:
Geometry, Gauge
Connection Types
Material Selection
Composite Layup

Step 3: Build up Performance Models:
Stiffness (NASTRAN)
Strength (ABAQUS)
Durability (NASTRAN + nCode)
Impact (LS-DYNA)
Variable Cost (MS-Excel)

Step 4: Apply Material Properties to all Performance Models

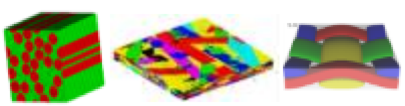
Step 5: Run All Performance Modes / Evaluate Against Criteria

Step 6: Construct Response surface

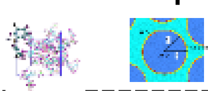
The complete process has been implemented in modeFRONTIER. Testing on a sample problem shows some bottlenecks and infrastructure (license) challenges.

CF Composite Design
CF, resin property
Fiber volume fraction
Fiber shape, diameter
SMC chip size
Fabric architecture
Others ...

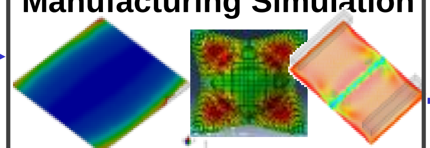
Parametric RVE Lib for material properties, failure criterion



MDA for Interphase

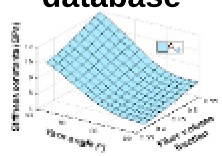


Manufacturing Simulation

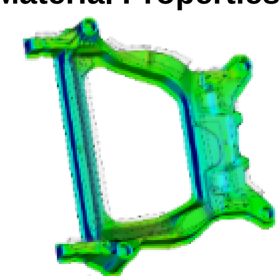


SMC Molding (Moldflow)
UD & Woven Preforming (LS-DYNA)
Local Fiber Orientation

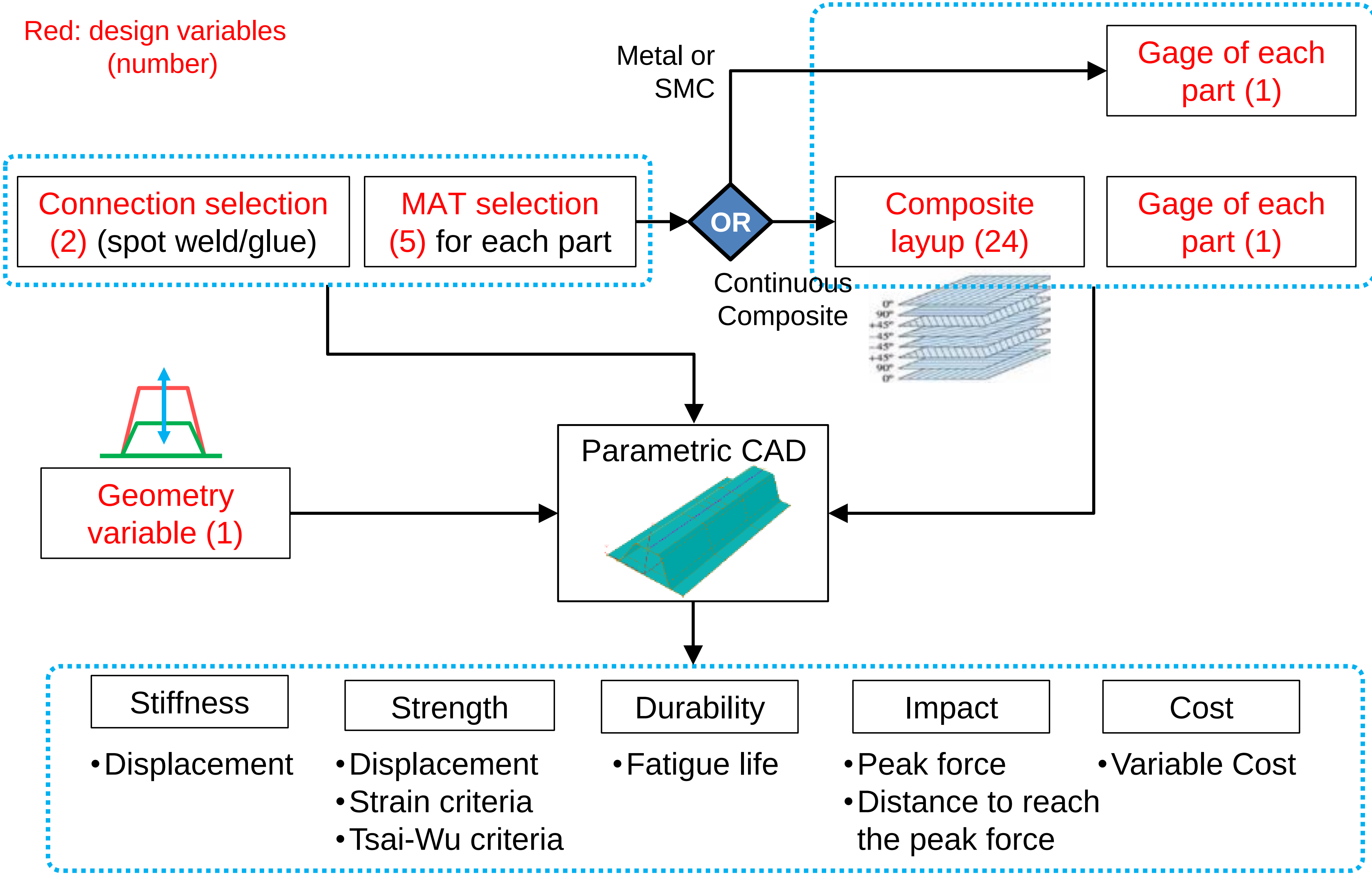
Metamodel database



Manufacturing Dependent Local Material Properties

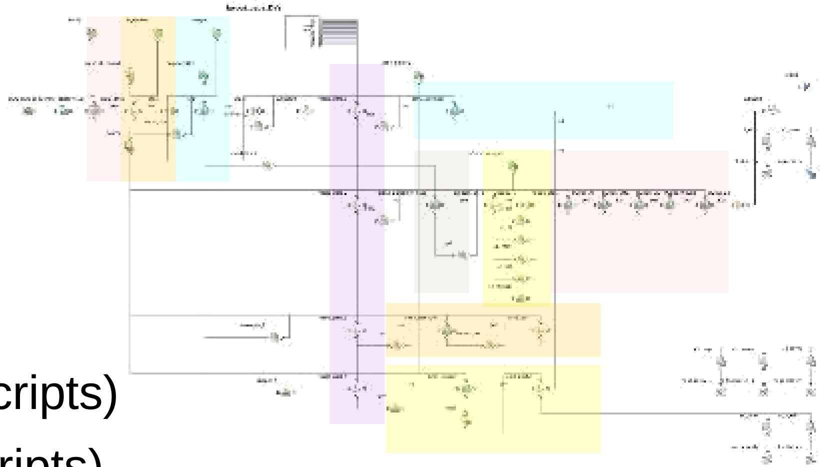


Accomplishments: Process Integration on Hat Section



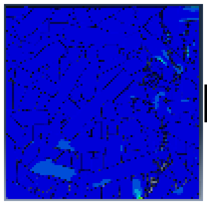
Accomplishments: Process Integration & Optimization

- Developed integrated modeFRONTIER workflow on Ford's High Performance Computing Platform, LINUX based using multiple CPUs.
- This work demonstrates the process integration techniques that will be applied to full subframe design.
- The workflows integrate the following modules:
  - Parametric CAD (SFE)
  - Composite layup generator (Jython scripts)
  - FEA Model Preprocessing (HyperMesh TCL scripts)
  - Mapping of local material properties (MATLAB)
  - Metamodeling (MATLAB)
  - Stiffness (NASTRAN)
  - Durability (NASTRAN + nCode)
  - Strength (ABAQUS)
  - Impact (LS-DYNA)
  - FEA postprocessing scripts (Jython scripts)
  - Variable Cost (MS-Excel → Jython scripts)



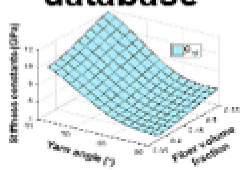
Accomplishments: ICME Model Validation & Accuracy

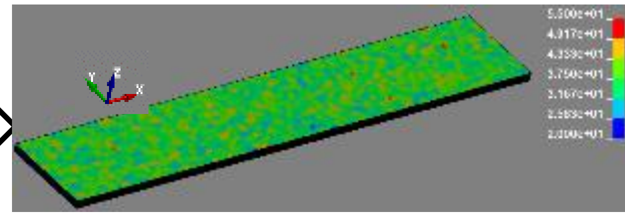
Example: 4-pt bending test with chopped CF SMC material



Microscale RVE for SMC

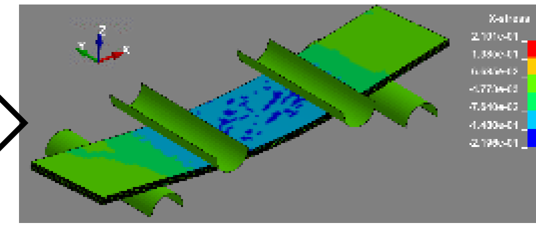
Metamodel database





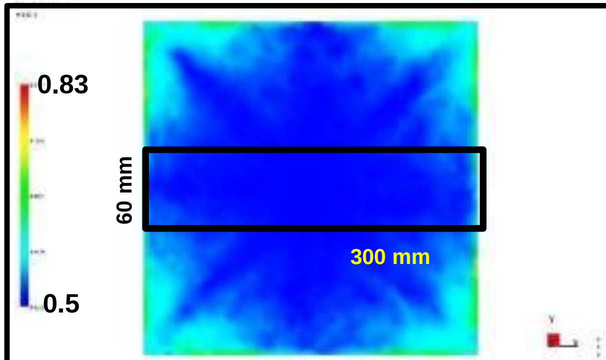
Local properties prediction

C_{11} component (in GPa) in C_{ij} elasticity matrix



Simulation in LSDYNA with MAT157

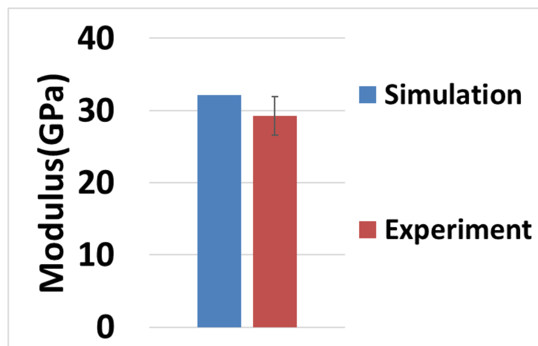
σ_{xx} (in GPa)



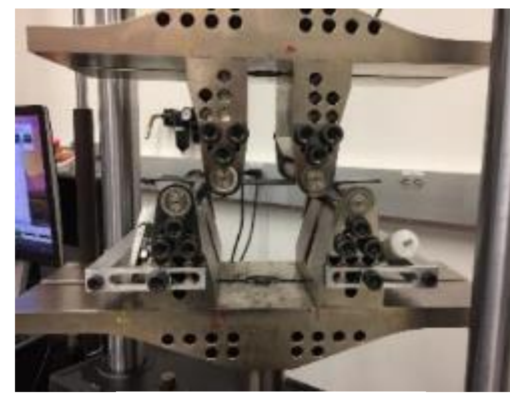
Fiber orientation prediction from Moldflow

(1st principle value of fiber orientation tensor)

Manufacturing simulation



Error in flexural modulus simulation vs. experiments: 9.9%



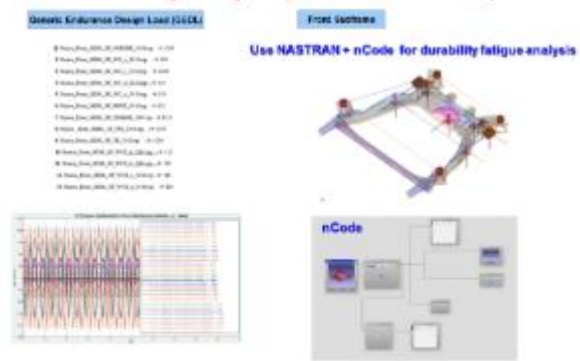
4-pt bending test

Integration of manufacturing process with structural performance

Accomplishments: Subframe Design, Performance Validation and Cost Analysis

Linear Static Stiffness Analysis

Durability Analysis (NASTRAN + nCode)



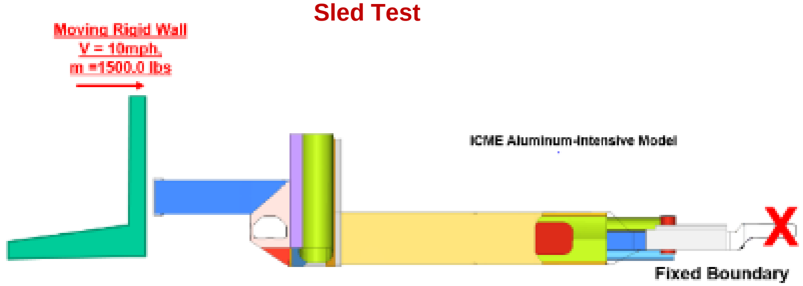
Global Suspension Strength (GSS) analysis

1-Stiffness (NASTRAN)
Requirements are global and local stiffness

2-Durability
(NASTRAN + nCode)
Requirements are 15 year life

3-Strength (ABAQUS)
Requirements are safe
"limp mode," no separation

Component Frontal Sled Test



4-Impact (LS-DYNA)
Requirements are load range and energy absorption

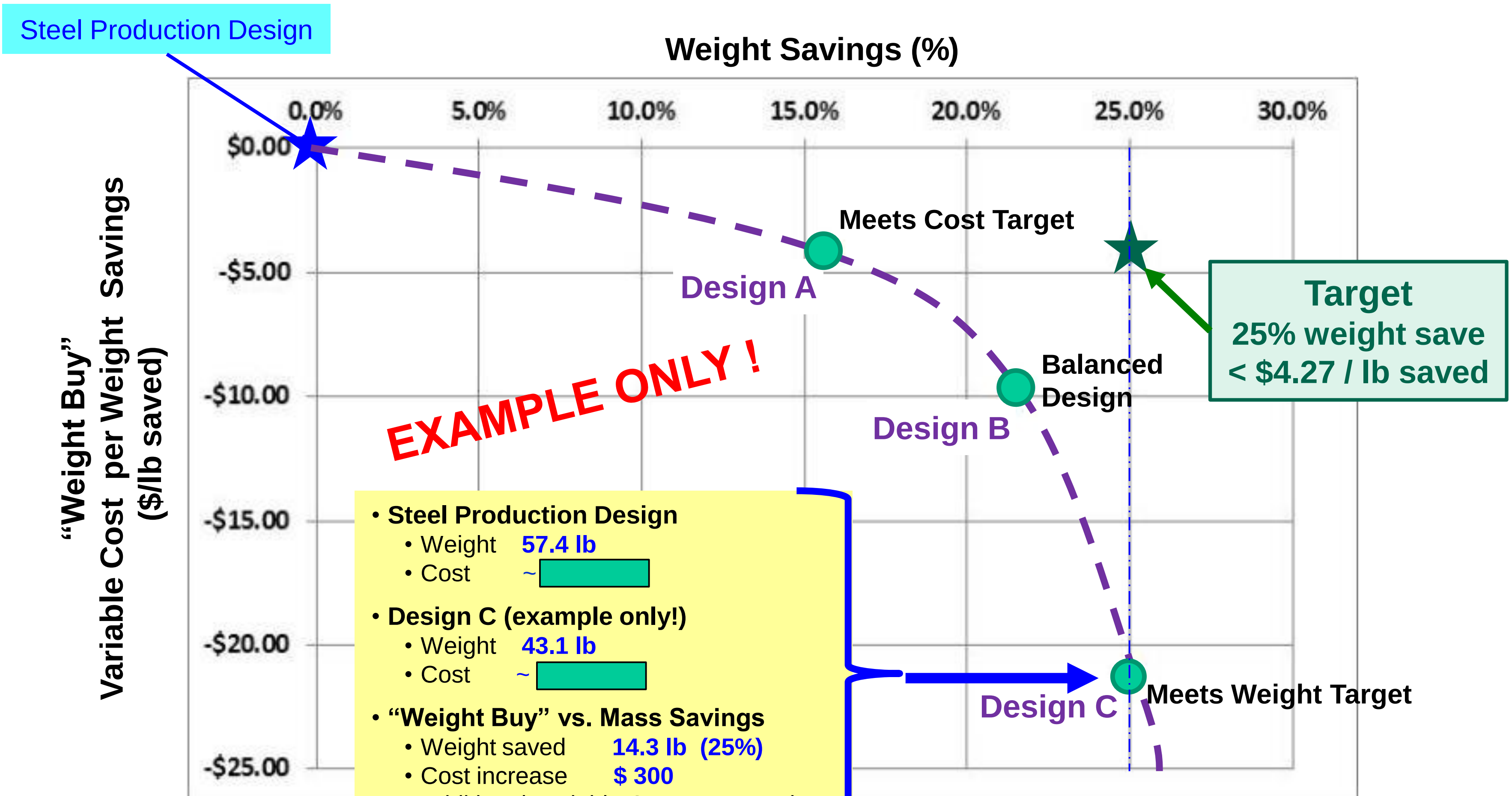
Variable Cost Analysis

5-Cost (Excel, Scripts, Hyperwork)
Estimate Variable Cost

images are for example only, representing the performance analyses

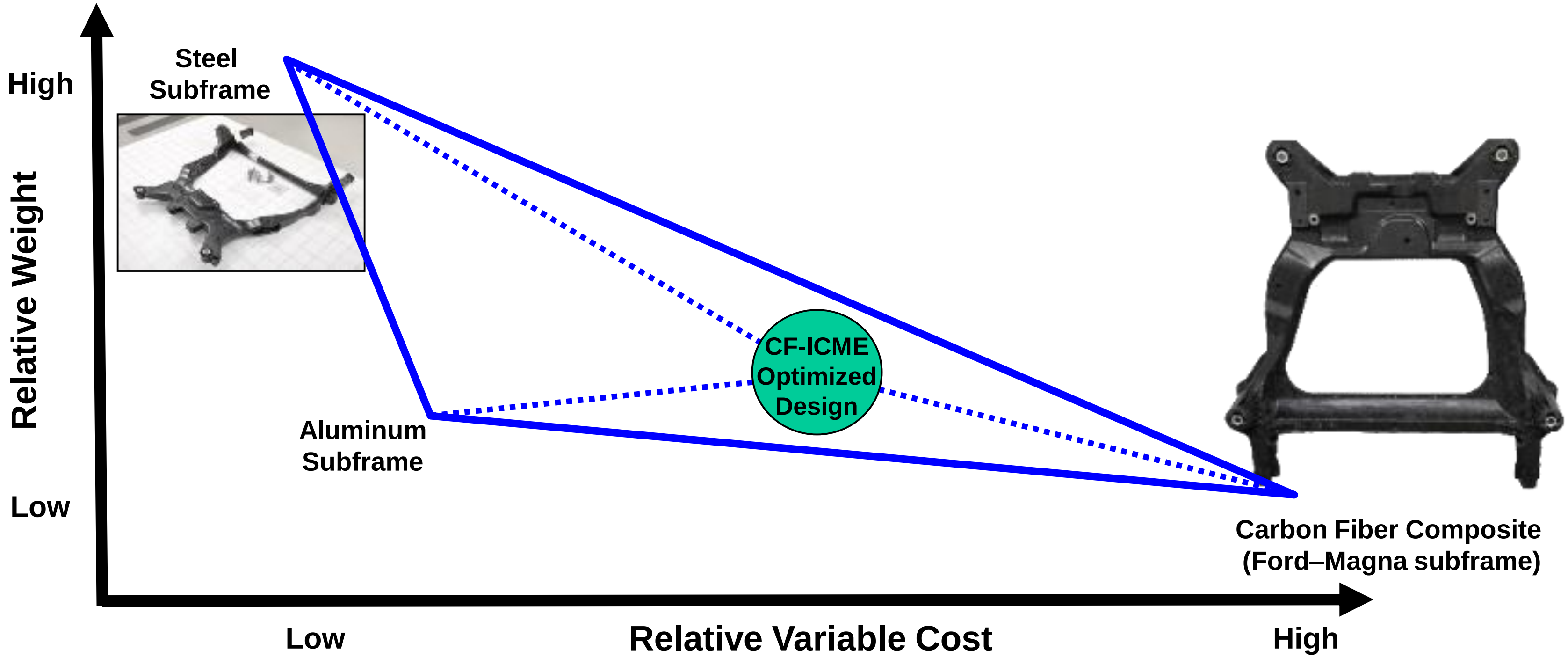
Accomplishments: Weight and Cost (Example)

Approach: Develop three designs to investigate the mass savings vs. cost relationship for carbon fiber subframes.



- **Steel Production Design**
  - Weight **57.4 lb**
  - Cost ~
- **Design C (example only!)**
  - Weight **43.1 lb**
  - Cost ~
- **"Weight Buy" vs. Mass Savings**
  - Weight saved **14.3 lb (25%)**
  - Cost increase **$ 300**
  - Additional Variable Cost per Pound of Weight Saved **21 $/lb**

Accomplishments: Cost Model for MDO



Variable Cost = **Material Costs + Purchased Parts + Labor + Burden + Markups**

Material Costs
Carbon Fiber: $5 / lb
Carbon fiber composite:
- X% carbon fiber
- (1-X)% epoxy resin
- Processing cost
- Overhead

Steel at $0.35 - $0.60 / lb
Aluminum at $1.75 - $2.10 / lb

Purchased Part Costs
Purchased Parts include adhesives, grease, screws, rivets, bushings, etc.

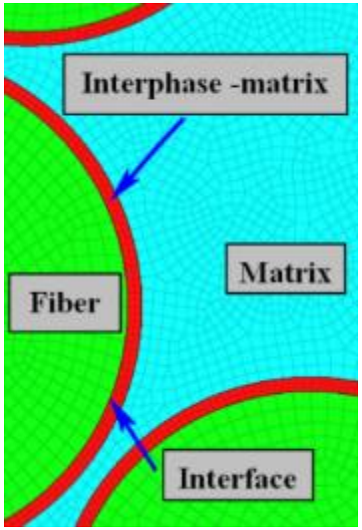
Burden/Overhead Costs
Production line operating cost
Depreciation, Insurance, Floor space, Utilities, MRO – Maint/Repair/Other

Labor Costs
Direct/Indirect/Fringe
Material Handling
Machine Operators
Machining, Assembly

Markup Costs
SG&A (Sales, Admin, etc.)
Profit, End Item Scrap,
Value Add on Purch Parts

Responses to Previous Year Reviewers' Comments

- While reviewers praised the micro-scale to macro-scale approach to the complexity of composites modeling, there was a question concerning the value of the molecular dynamics (MD) interphase strength predictions.
  - In this project, the sizing is assumed accommodating to epoxy resin and treated as insufficient cross-linked epoxy resin. MD simulation is conducted to predict the effect of insufficient cross-linking resin. A general gradient model is developed to calculate the interphase properties based on the MDA results. By considering the interphase properties in RVE model, the material deformation prediction is in much better agreement with experiments. However, if the sizing is incompatible with the resin, the junction between sizing and epoxy resins will become much weaker. The interphase properties will be subject to change.



RVE model with interphase property input from MDA

- A reviewer asked which aspect of composite processing would be most impactful in improving the overall predictability to better than the 15% target for this project.
  - Accurate predictions of fiber angle and waviness would improve overall predictability. This might require more mature uncertainty quantification.
- A reviewer asked the team to clarify which aspects of these modeling efforts differ from ICME efforts in the aerospace industry.
  - We integrate a suit of predictive computational models that link the materials design, manufacturing processes and structural performance requirements to enable optimal design and manufacturing of CFRP structural components. We improved crash modeling techniques to capture the composite failures in different modes.

Partners, Collaborators and Coordination

Partner	Weekly	Biweekly	Quarterly
Ford Motor Company: automobile manufacturer, composite characterization, process simulation, subframe design and performance analysis, uncertainty and optimization	X	X	X
DOW Chemical: material manufacturer, material preparation, resin and composite characterization, compression molding simulation	as needed	X	X
Northwestern University (five professors and their students): resin and composite characterization, MDA, non-orthogonal model for preforming, RVE, uncertainty and optimization	X	X	X
NIST/University of Maryland: resin and composite characterization, DSpace materials database management	as needed	X	X
CAE software development, model development and implementation, Moldflow, LS-DYNA, nCode, modeFRONTIER	as needed	X	X

Software Tech Transfer

LSTC model implementation in LS-DYNA

New Material Models:

MAT_293_COMPRF
for carbon fiber prepreg forming simulation, released 2nd quarter 2017.

MAT_278_CF_MICROMECHANICS
for carbon fiber prepreg forming simulation, released 1st quarter 2017

Material Model Improvements:

MAT_277 ADHESIVE_CURING_VISCOELASTIC,
material model for resin curing processing, released 2nd quarter 2016.

MAT_054 ENHANCED_COMPOSITE_DAMAGE,
material model for carbon fiber crash simulation, released 1st quarter 2018.

New Features:

Mapping Interface program for utilizing molding simulation result from Moldflow and MoldEx3D for crash simulation released in LS-Prepost in 1st quarter 2018

New LS-DYNA keyword *DEFINE_LAYER for automating the prepreg forming model setup, released in 4th quarter 2017

Moldflow (software from Autodesk)

SMC Compression Molding Improvements in 2018 Moldflow version:

Flexible charge placement, Improved solution stability for complex part designs, New switch over to press force controlled filling

nCode (software from HBM Prenscia)

Composite fatigue prediction module for continuous carbon fiber composites

Remaining Challenges and Barriers

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

- **Crush Simulation**
  - Simple method to calibrate the post failure parameters;
  - Computational efficiency;
- **Multi Scale Modeling**
  - Computational efficiency
  - Accurate, robust failure criteria.
- **Fatigue**
  - Standardized testing methods
  - Multiaxial fatigue testing and modeling
- **Multi Disciplinary Optimization (MDO)**
  - Computational efficiency of manufacturing and performance models
  - Computing infrastructure, license servers, etc.
- **Lightweight and cost effective subframe design**
  - Meet weight target: weight reduction > 25%
  - Meet cost target: cost increase ≤$4.27/lb of weight saved
  - Identify primary cost drivers

Future Work to December 2018 END

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

Materials characterization	• Material characterization of 400gsm twill and 660gsm plain woven composites	30-June
RVE	• SMC strength prediction and validation	30-Sept
Preforming	• NCF prepreg preforming modeling and validation • Methodologies in generating reliable inputs for NCF RVE & metamodeling	30-June
Crash	• Apply the develop approach to complex subsystem crash simulation	30-Sept
Fatigue	• Fatigue tests for woven composites	30-June
Uncertainty	• The full uncertainty quantification package with user friendly interface	30-Sept
Integration and Optimization	• Complete the software integration of ICME models for optimization in modeFRONTIER	30-June
ICME-based Design & Optimization	• From modeFRONTIER MDO design three subframes, one meeting cost target, one meeting weight target and a third “balanced” design	30-Sept

Summary

- **CF ICME is an exciting project**
  - Guides the carbon fiber composite manufacturing process, suggests material design/ architecture, suggests quality control key metrics, i.e., fiber curvature, misalignment, tow size, etc.
  - Improves CAE prediction accuracy for improving design. Relates local material properties to local design needs.
- **Accomplishments**
  - Demonstrated compression molding simulation for full subframe using chopped carbon fiber sheet molding compound material.
  - Completed testing and constant fatigue life diagrams for unidirectional carbon fiber composites, tested on laminated flat plaques.
  - Completed an accurate meso-scale approach for CF composite crash simulation to predict axial crush and beam bending failure modes
  - Completed a systematic approach to quantify the uncertain at different scale and the propagation across the length scales
  - Incorporated full set of ICME tools into modeFrontier, exercised example Top Hat design.
- **Future Work, (Any proposed future work is subject to change based on funding levels)**
  - Complete modeFRONTIER multi disciplinary optimization for three subframe designs.
  - Identify gaps and areas for improvements in the ICME workflow.
    Molding simulation, local material mappings,
  - Increase efficiencies in multiscale model computations.
  - Complete weight and cost predictions for three subframe designs.
  - Complete documentation