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

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Ford Motor Company
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Project ID: LM101

Overview

Timeline

- Project start date: Oct. 1, 2014
- Project end date: Dec. 30, 2018
- Percent complete: 30% complete

Budget

- Total project funding
  - DOE share: $6,006,000
  - Contractor share: $2,574,000
- Funding in FY 2015: $1,774,093
- Funding for FY 2016: $1,491,260

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:
  - Capable of achieving ≥25% weight reduction
  - Meet packaging, safety and durability requirements of vehicle structural members
- Cost:
  - Cost increase ≤$4.27/lb of weight saved

Partners

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

Relevance And Projective Objective

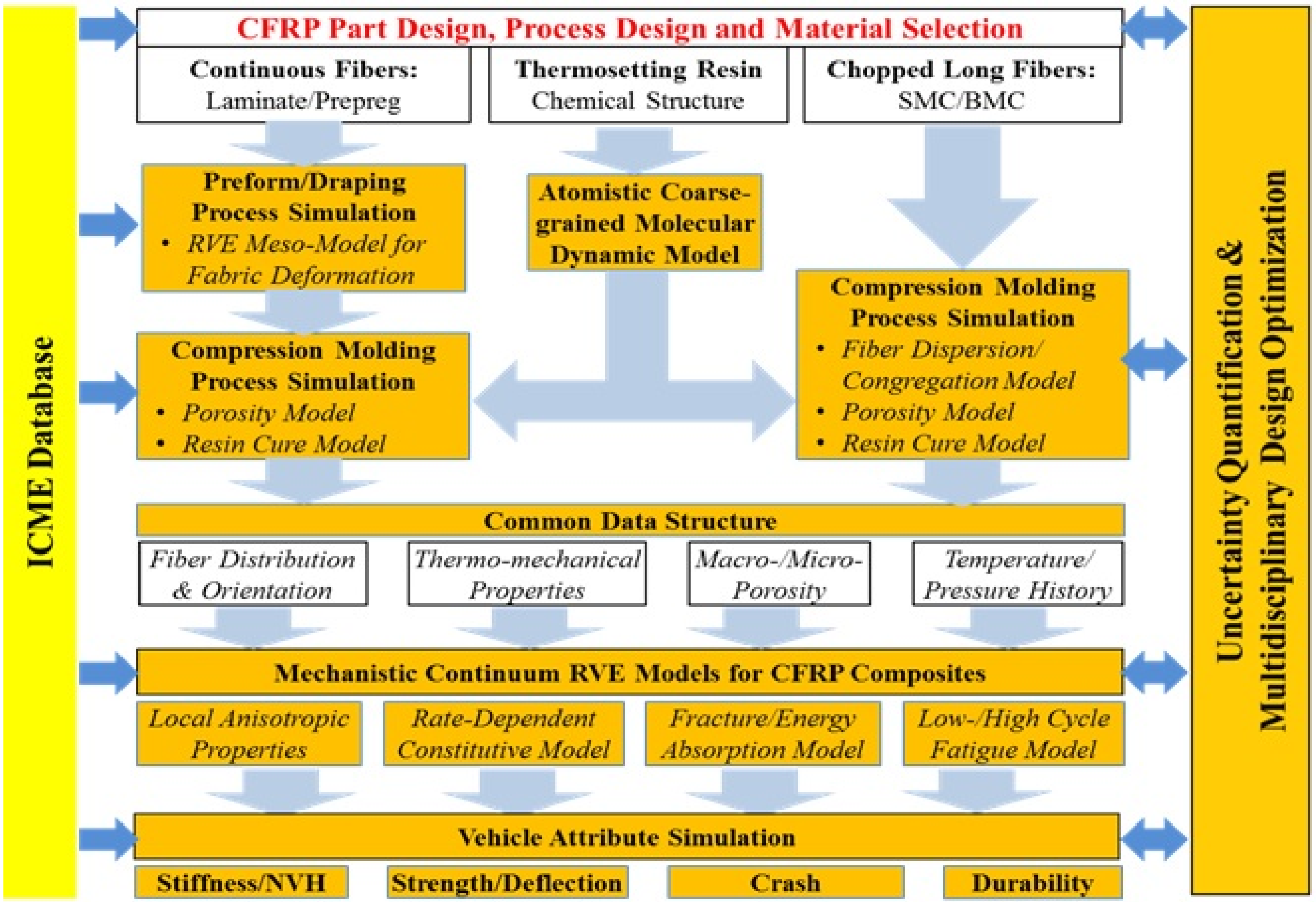
- Overall Objectives:
  - Develop Integrated Computational Materials Engineering (ICME) Tools
    - Simulate the manufacturing process
    - Predict part and assembly attributes (safety, durability and NVH)
      - Material models based on material design and manufacturing processes
      - CAE analysis accounting for local material variations due to process influences
    - Error of model predictions vs experimental measurements ≤15%
    - Optimize component design in both performance and process for most efficient usage of material, to achieve/exceed performance, weight and cost targets
  - Design and optimize a carbon fiber front subframe for a five passenger sedan using ICME models developed (CAE only, no prototypes or vehicle tests)
    - Capable of achieving a ≥25% weight reduction to address the DOE 2030 targets
    - Cost increase ≤$4.27/lb of weight saved to address the DOE 2030 targets
    - Meet structural performance in safety, strength/durability and NVH
- Objectives (October 2014–March 2016)
  - Develop/characterize carbon fiber composite which meet performance requirements for vehicle lightweighting to reduce greenhouse gas emissions and dependency on foreign oil
  - Develop and validate ICME models and integrate ICME modules & processes

Milestones

Milestone	Date	Status	Type
Test matrix and plan finalized	12/31/2014	Complete	Technical
Database structure established	3/31/2015	Complete	Technical
Validation part molding plan established	6/31/2015	Complete	Technical
Resin and carbon fiber properties meet performance requirement	**9/30/2015**	Complete	Go/No Go
Resin and carbon fiber characterization completed	12/31/2015	Complete	Technical
Preform/draping model correlated	3/31/2016	Complete	Technical
Fiber interfacial properties completed	6/30/2016	On Track	Technical
The framework for linkage of ICME models accomplished	**9/30/2016**	On Track	Go/No Go

Approach/Strategy

ICME Strategy



Go/No Go Milestones

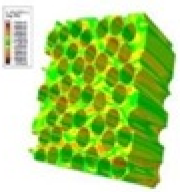
Q4/2015	Resin and fiber properties meet performance requirements	Complete
Q4/2016	The framework for linkage of ICME models accomplished	On track

Approach: Task Teams and Task Integration

Task 1 Material and Material Characterization

Task 2 Molecular Dynamic Analysis (MDA)

Task 3 Multiscale Modeling Representative Volume Element (RVE)



Task 4 Forming Analysis (laminates)

Task 5 Molding Analysis (chopped fibers)

Task 6 Crash Analysis
Task 7 Fatigue Analysis

Task 8 Data Structure, Process Integration, Uncertainty and Optimization

Material Design → Compression Molding Analysis (Moldflow, LS-DYNA) → Crash(LS-DYNA) / Durability (nCode) / NVH → Design Optimization (modeFRONTIER)

Accomplishments-Material

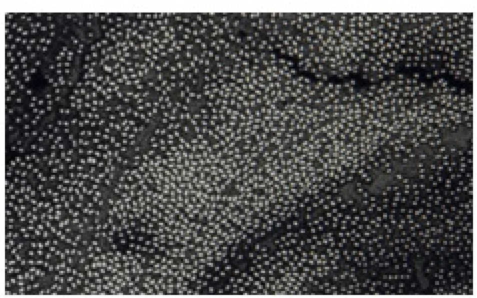
- Material system
  - Developed by Dow Chemical
  - Matrix: Thermoset epoxy resin A
  - Vacuum assisted compression molding process is used in order to achieve aggressive cycle time and cost requirements (cycle time<5 minutes)

Fiber System

Continuous	Chopped
AKSACA A42 12k/24k	AKSACA AC1101

Fabric Architecture

Continuous	Chopped
UD NCF Woven	SMC



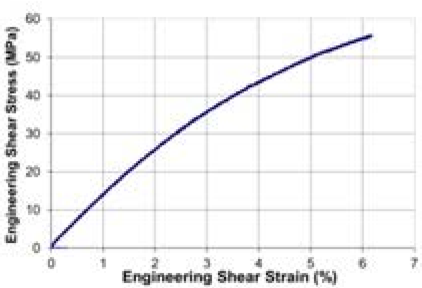
Optical image of UD composite

Properties of developed CFRP

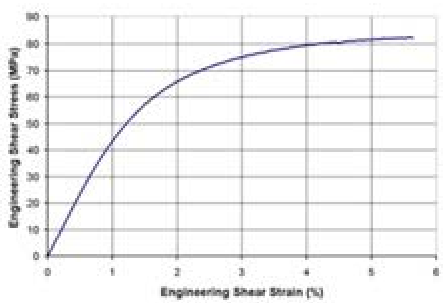
Property	Longitudinal	Transverse
E	125 GPa	8.89 GPa
v	0.33	0.023
F_t	2100 MPa	61.7 MPa
V_f	~50% (measured by bulk density)	

Accomplishments-Material

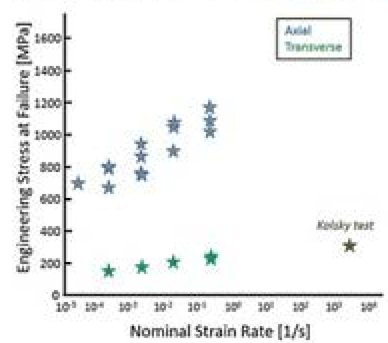
- Mechanical properties of the composite and resin measured for unidirectional (UD)
  - Resin
    - Tensile, compression, shear
    - Fracture toughness
    - Viscosity, MDA measurements, high strain rate, elevated temperature
  - Composite
    - Tensile, compression, shear
    - Microstructure measurements, delamination



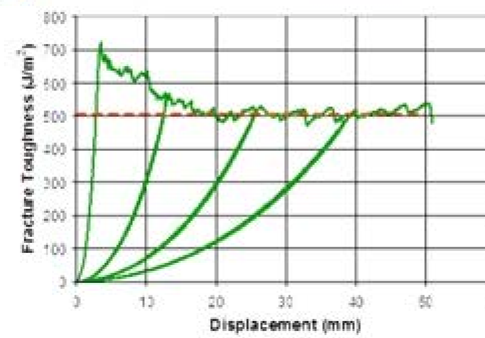
Resin characterization



Composite shear test



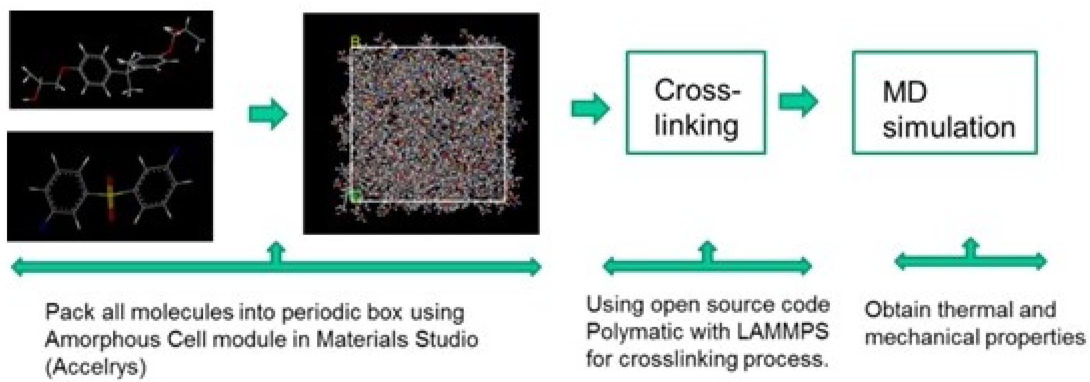
Compression at high strain rate



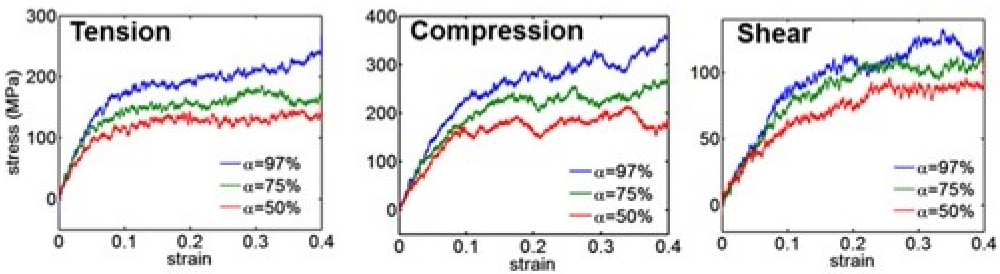
Fracture toughness test

Accomplishments-MDA

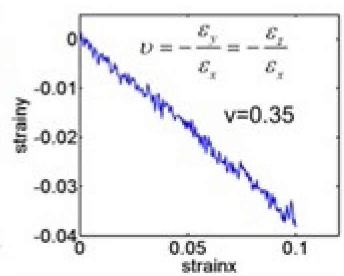
- Molecular Dynamic Analysis (MDA)
  - Completed the built-up of an atomistic model to study the thermo-mechanical properties
  - Predicted material properties: stress strain curve, glass transition temperature (consistent trends with existing experimental data)
  - Studied fracture behavior of resin
- MDA model



- The predicted material properties



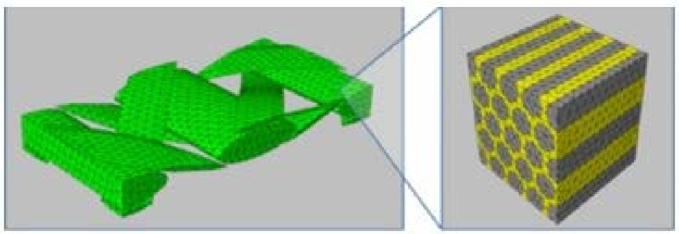
Modulus and Stress-Strain Curves

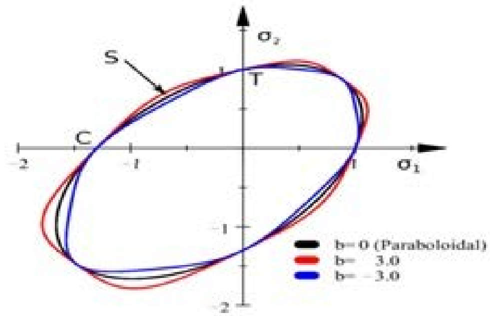


Poisson's Ratio

Accomplishments-Multiscale Modeling

- Implemented RVE UD model with random fiber distribution
  - Matrix: anisotropic plasticity, temperature and strain rate dependent
  - Matrix and fiber failures are considered
  - Yield and hardening of resin are related to MDA predictions
- Developed RVE for woven fabric



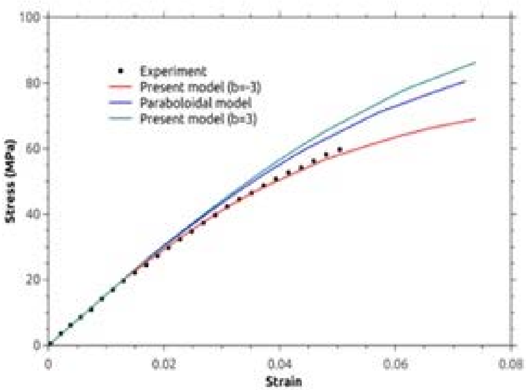


Proposed Matrix Yield Surface

$$f(\boldsymbol{\sigma},C,T)=a\left(J_2^{\,3}+bJ_3^{\,2}\right)^{1/3}+2(C-T)I_1-2CT$$

$$b=\frac{1}{4}\left(\frac{(3S)^6}{(CT)^3}-27\right) \qquad a=6\left(\frac{27}{4b+27}\right)^{1/3}$$

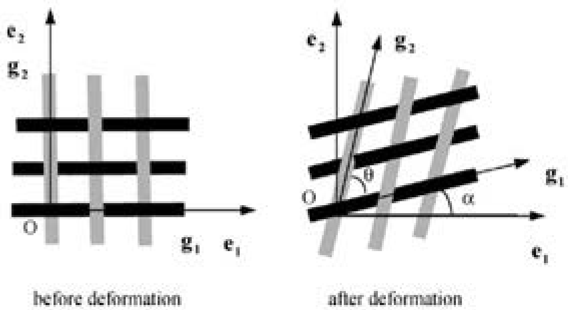
Shear yield strengths



Improvement of proposed matrix model

Accomplishments-Preforming

- **Accomplishments**
  - Developed a non-orthogonal model to better predict the fiber orientation and winkling for woven prepreg forming
  - Performed tests on dome tool to validate the non-orthogonal model

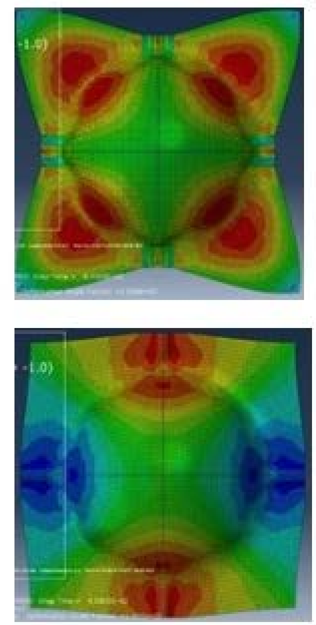


Fiber orientation change due to forming

Validation experiments

Single dome model validation

Testing

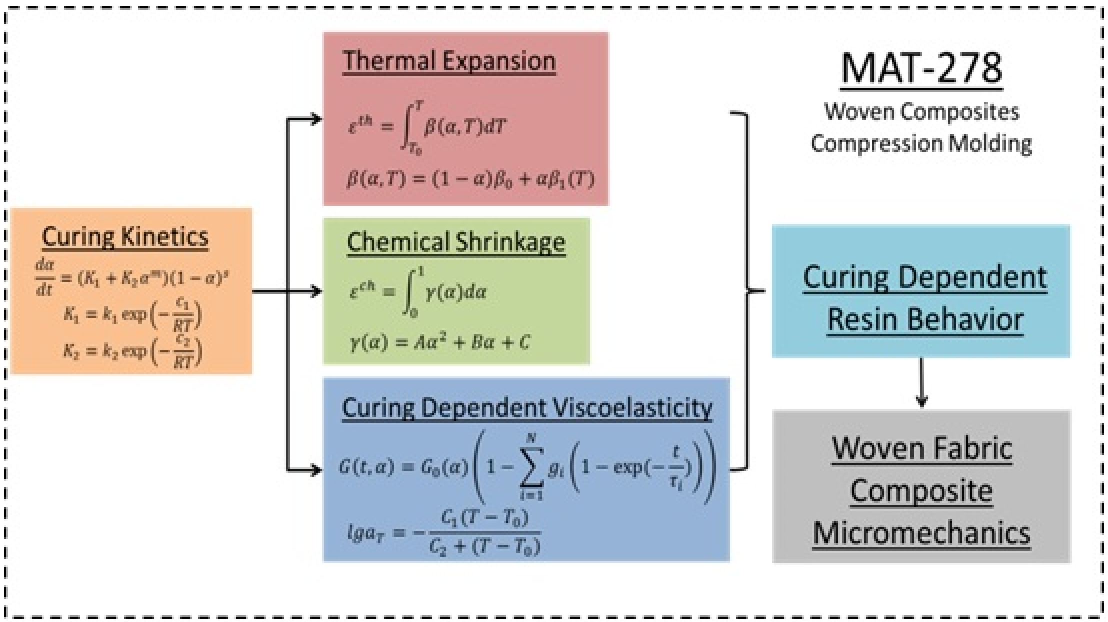


Simulation

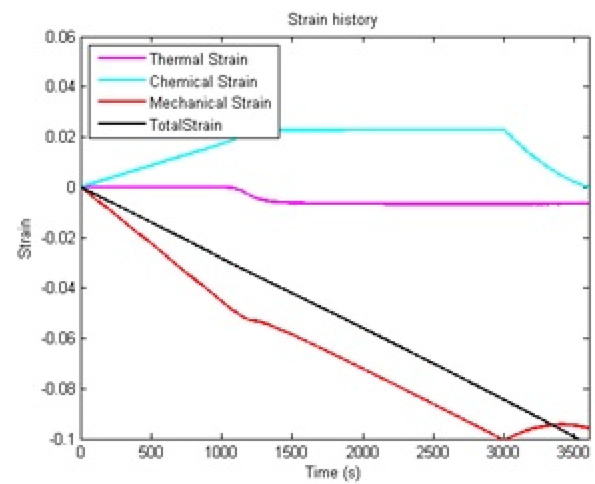
Fiber orientation

Accomplishments-Curing Model

- **Accomplishments**
  - An integrated material model (MAT-278) has been developed and implemented in LS-DYNA for compression molding of woven fabric CFRP
  - Experimental validation is undergoing



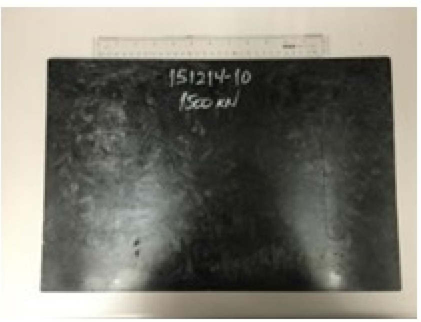
Implemented chemo-thermal-viscoelastic model

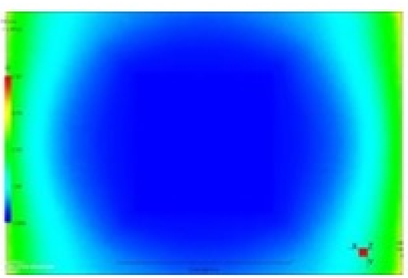


Evolution of different types of strain

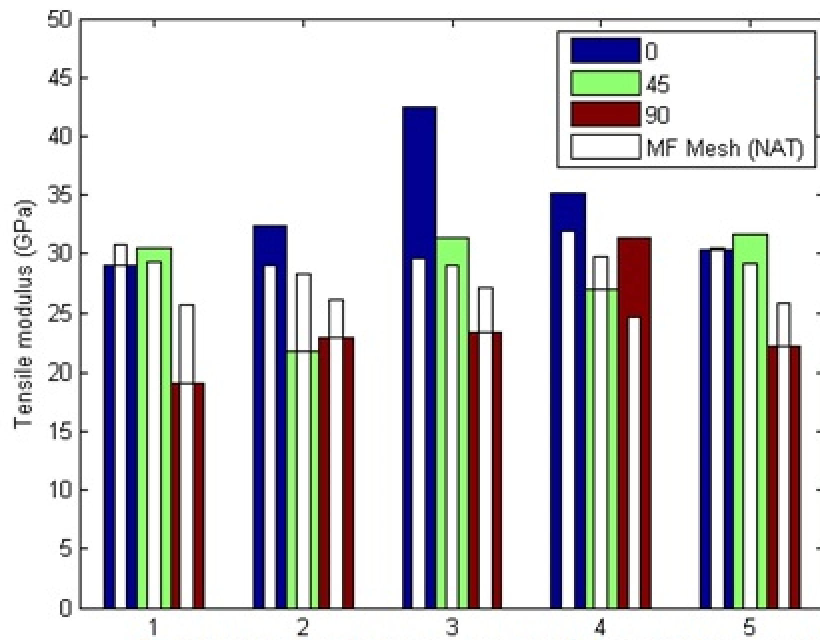
Accomplishments-Molding of SMC

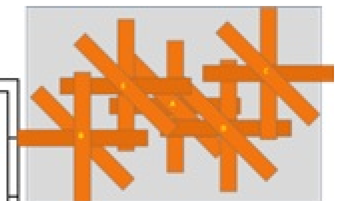
- **Accomplishments**
  - Completed molding trials on flat plaques to improve SMC compression molding simulation in Moldflow
  - Key outputs from Moldflow simulation are compared with experimental data
    - filling time, press force/displacement, tensile modulus at different locations etc.
  - Second set of the molding trials will start soon





Filling pattern comparison

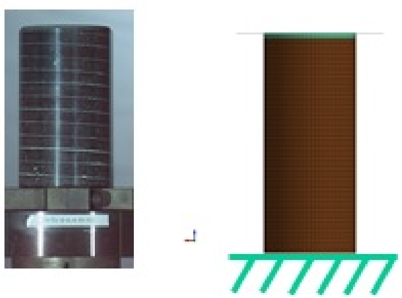




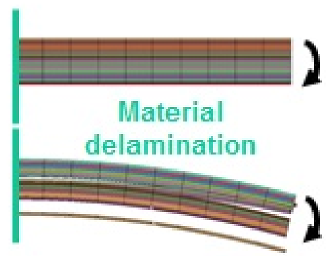
Comparison between modulus by test and prediction based on Moldflow (colored: experiment, white: modeling)

Accomplishments-Crash Analysis

- **Accomplishment**
  - Using RVE to predict elastic properties to be used in MAT 54/58 for crash analysis
  - Use meso-model to simulate a crash test
  - Proposed a new shell element to better account for delamination



Test and simulation of a UD tube crash



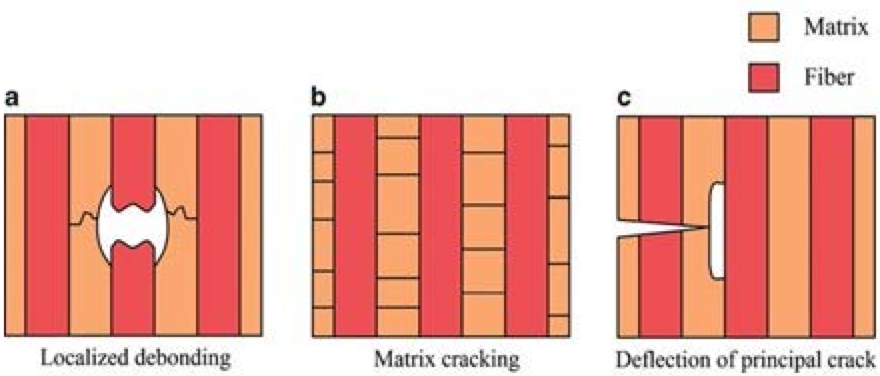
Issues of existing shell element in modeling delamination

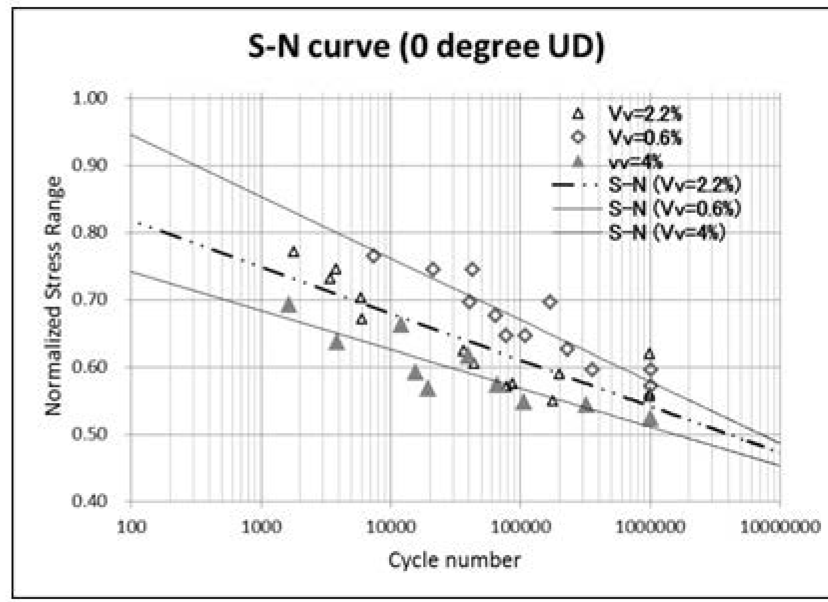
Linear elasticity for MAT 54/58

	E11	E22	G12	G23	v12
Experiment (Gpa)	125.255	8.894	4.846		0.3267
Calculated (Gpa)	125.906	8.615	4.867	2.735	0.3214
Difference (%)	0.52%	3.14%	0.43%		1.62%

Accomplishments-Fatigue Analysis

- **Accomplishments**
  - Agreed upon the strategy of a CFRP modules in nCode
  - Performed fatigue tests (over 100 specimens)
    - Studied influence of test frequency
    - Studied impact of microvoids on fatigue
    - Fatigue tests in 0°, 90° and 45° to fiber orientation

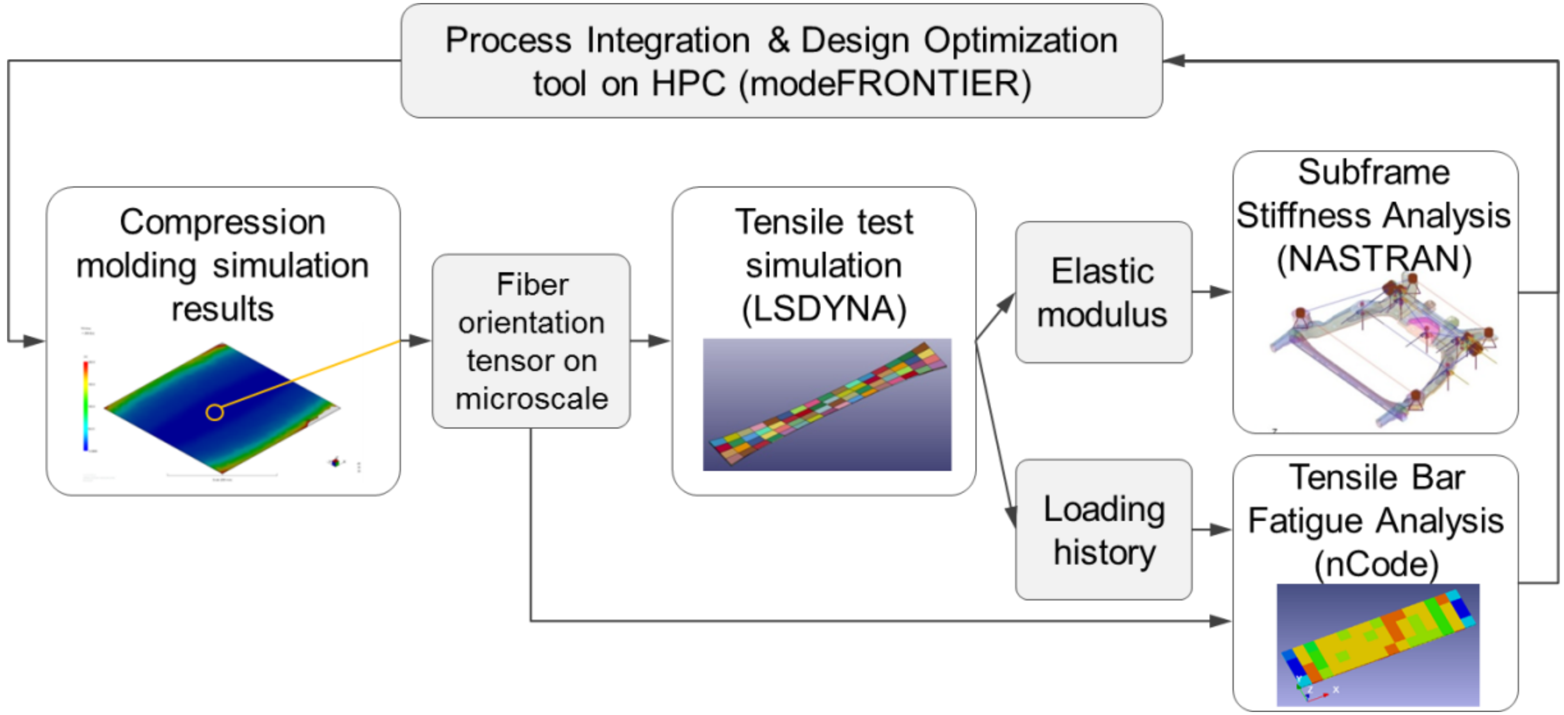




Impact of microvoids on fatigue

Accomplishments-Process Integration

- **Accomplishments:** Integrated the following modules/models into one workflow (managed by modeFRONTIER)
  - Compression molding simulation results – fiber orientation tensor (Moldflow)
  - Material stress-strain relation (tensile bar simulation in LS-DYNA)
  - Subframe stiffness (NASTRAN)
  - Coupon fatigue (nCode)



Responses to Previous Year Reviewers' Comments

This project was not presented at the 2015 Annual Merit Review

Partners and Collaborators

Ford Motor Company: automobile manufacturer, composite characterization, process simulation, subframe design and performance analysis, uncertainty and optimization

DOW Chemical: material manufacturer, material preparation, resin and composite characterization, compression molding simulation

Northwestern University (5 professors and their students): resin and composite characterization, MDA, non-orthogonal model for preforming; RVE, uncertainty and optimization

NIST/University of Maryland: resin and composite characterization; DSpace management

LS-DYNA

nCode ...an HBM brand

Autodesk Moldflow

modeFRONTIER

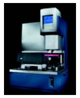
CAE software development, model development and implementation

Remaining Challenges and Barriers

- CFRP as structural material are rapidly evolving
  - Material and compression molding process of SMC is still under development
  - New CAE modules in major application software need development and improvements
    - Compression molding module in Moldflow needs validation
    - No existing FEA modules in LS-DYNA to handle delamination
    - nCode for CFRP is still under development
- Experiments for validation of models
  - Single fiber fragmentation tests to validate MDA predictions
  - 3D analysis of strain fields in prepreg using DIC to further validate material model used in forming analysis
  - Analysis of damage through microstructural observation to inform failure criteria for material models
- Material failure model and its relation with material microstructure and processes
  - Incorporation of failure into models
    - related to microstructural features (voids, etc.)
    - predicted by the curing and molding analyses
  - Incorporation of MDA modeling results into RVE models
- Predictions of material uncertainty and its transfer from length scale to another
- Process integration and seamless data transfer from one analysis to another

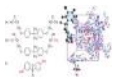
Planned Work for FY2016/17

Materials characterization



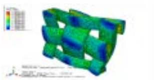
- Molding and characterization of woven plaques
- Elevated temperature and high rate testing of composite and resin
- Single fiber fragmentation tests and component-level validation tests

MDA



- Develop resin curing curve and model resin and fiber interphase failure
- Design validation tests of MDA models

RVE



- Complete RVE for woven laminate and chopped fiber, validate RVE considering failure
- Quantify property variations due to random fiber distribution and material uncertainty

Preforming

- Implement non-orthogonal the model in LSTC LS-DYNA
- Experimentally validate the model: fiber orientation and winkling

SMC molding

- Complete 2nd set of experiments to validate/improve Moldflow molding module
- Validate fiber orientation with microscopic images on flat plaques

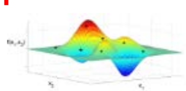
Crash

- Work with LSTC to develop elements which account for delamination
- Use nonlinear RVE for material 261/262, validate predictions with double dome tests

Fatigue

- Complete fatigue tests needed for CFRP modules in nCode
- Perform component tests to evaluate implemented CFRP modules

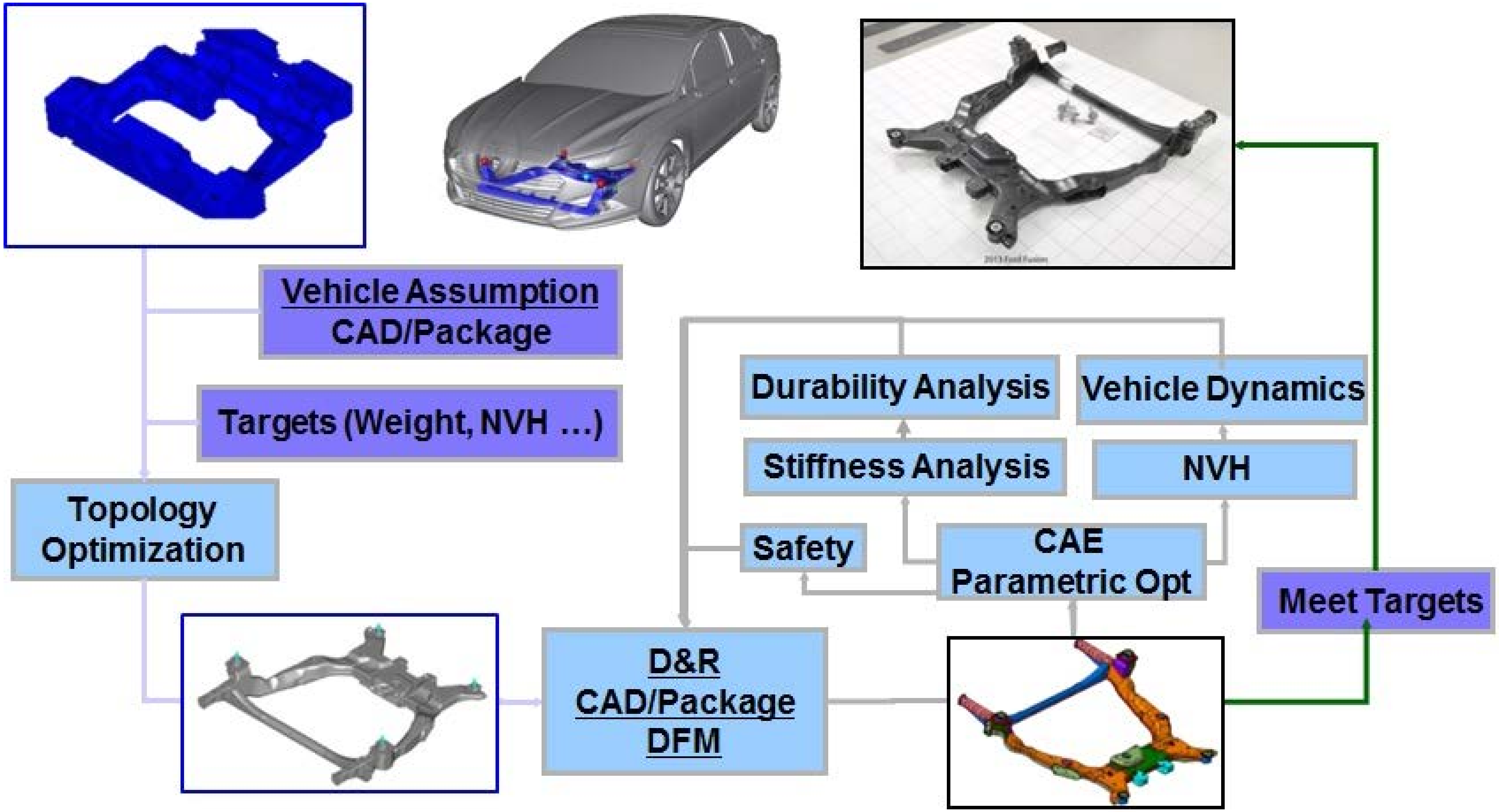
Process integration and optimization



- Establish an integrated optimization workflow to optimize the design parameters of material, manufacturing, component structure simultaneously
- Complete the framework for linkage of ICME models using modeFRONTIER

Future Work: CF Subframe CAE Design

(CAE only, no prototypes or vehicle tests)



DOE Targets:
- Achieving ≥25% weight reduction
- Cost increase ≤$4.27/lb of weight saved

Summary

- CF ICME is a exciting project
  - Speed up the application of CFRP in vehicle structures for light weight
  - Improve the CAE prediction capability, design optimization both in performance and processes, achieving most efficient usage of material, with high quality and low cost
- ICME is advanced predictive CAE tool
  - Based on experimental data and basic physics, robust and accurate
  - Link material science, process simulation and performance analysis
  - Optimize design and manufacturing process to improve quality and reduce cost
- Accomplishments
  - Developed a resin and composite which meet performance requirement
  - Completed multiscale RVE model for UD, guided by MDA and validated by experiments
  - Proposed a non-orthogonal model for preforming analysis, validation tests are ongoing
  - Implemented a curing model in LS-DYNA as MAT278
  - Modules for chopped fiber compression molding, safety, durability models are on track
  - Identified the platform for common data structure and process integration.
- Future works
  - Complete, validate and implement proposed modules in relevant commercial software
  - Complete the framework for linkage of ICME models using modeFRONTIER
  - CAE design and optimize CFRP subframe