Predictive Engineering Tools for Injection-Molded Long-Carbon-Fiber Thermoplastic Composites

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Project ID: LM083

Overview

Timeline

- Project start date: Sept 11, 2012
- Project end date: Sept 30, 2014
- Percent complete: 20 %

Barriers

- Barriers addressed

1. Manufacturability: Injection-molding long-carbon-fiber thermoplastics (LCFTs) is highly challenging
2. Predictive modeling tools need validations for LCFTs
3. Tooling and prototyping: Costs of mold tooling and retooling

Budget

- Total project funding: $2,082,822
  - Federal Funding: $1,001,000
  - Cost share: $1,081,822
- Funding received in FY12: $1,001,000
- Expenditures:
- FY14: $203.2K (cumulative federal dollars spent through March 2014)
- Cost share contributed: $397,949 (cumulative cost share through March 2014)

Partners

- Interactions / collaborations

1. PlastiComp: LCFT compounding, plaque molding, assisting in complex part study
2. Magna: Molding the 3D complex part
3. Toyota: Providing the 3D complex part, building fixtures, participating in cost/weight savings study
4. Purdue University: Fiber orientation and length measurements
5. Autodesk: Rheological/physical properties characterizations + process models improvements
6. University of Illinois: Consultant services

- Project lead: PNNL

Objectives - Relevance

- **Objective:** Advance the *predictive engineering tool* to accurately predict *fiber orientation and length distributions* in *injection-molded long-carbon fiber thermoplastic composites* for optimum design of automotive structures using these materials *to meet weight and cost reduction requirements*

- **FY14 Objectives:** Complete improvements, integration and validation of process models for fiber orientation and length distributions implemented in Autodesk Simulations Moldflow Insight (ASMI) for long-carbon-thermoplastic plaques
  - Complete compounding 30 wt% and 50 wt% LCF/polypropylene (PP) and LCF/polyamide 6,6 (PA66)
  - Complete injection-molding 30 wt% and 50 wt% LCF/PP and LCF/PA66 plaques
  - Complete rheological and mechanical tests for all 4 above compounds
  - Improve 3D fiber orientation prediction and implement reduced-order fiber-length model in ASMI for computational efficiency
  - Measure fiber orientation and length at selected locations on plaques for model validation
  - Validate ASMI mid-plane and 3D predictions for fiber orientation and length for the selected locations on plaques within 15% of the measured data

Collaborations and Coordination with Other Institutions

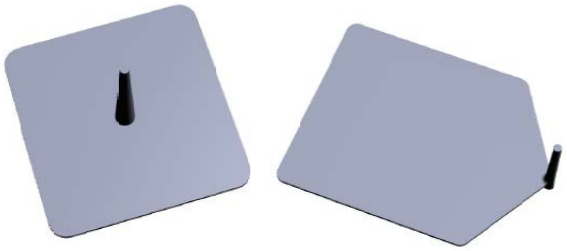
PNNL
- Overall project management
- Coordination of research activities
- Performs process modeling using ASMI for model validation
- Performs weight/cost reduction study

University of Illinois
- Provides consultant services to Autodesk for fiber length and orientation models improvement and integration

Autodesk
- Improves and integrates fiber orientation and length models for LCFTs in ASMI
- Performs rheological/physical property measurements
- Delivers a research version to PNNL for model validation
- Technical support to PNNL

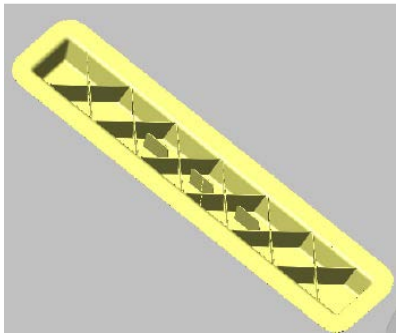
Phase I – PlastiComp Plaques study

Long-carbon-fiber/PP
Long-carbon-fiber/PA6,6



Purdue University
- Performs fiber orientation and length measurements on PlastiComp plaques and Toyota complex 3D part

Phase II
Toyota complex 3D part



PlastiComp
- Performs compounding LFTs
- Injection-molds test plaques using both LFT/D-LFT processing
- Provides consultant services for molding the complex part

Toyota
- Provides the complex automotive part
- Modifies preexisting mold
- Builds fixture to evaluate part stiffness
- Assists PNNL in weight/cost reduction study

Magna
- Participates in mold design
- Injection-molds the complex part

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FY14 Project Milestones

Quarter	Milestone Descriptions	Responsibility	Completed by	Status
FY14 Q1	PlastiComp to deliver 55 lbs of 30 wt% and 50 wt% LCF/PP and LCF/PA66 compound materials to Autodesk for material characterization that is within a 10% batch variation using loss on ignition mass comparison.	PlastiComp	12/31/2013	Completed
FY14 Q2	Deliver 320 edge and centered gated 7x7x0.125 inch plaques to PNNL per statement of work test matrix on 30 wt% and 50 wt% carbon fiber PP and PA resin systems.	PlastiComp	3/1/2014	Partially completed*
FY14 Q3	Autodesk to deliver material characterization report on shear flow, PVT, and mechanical property suite in udb file input for ASMI and PDF on the 30 wt% and 50 wt% PP and PA compound materials from PlastiComp for use in flow simulations in two and three dimensional part.	Autodesk	4/1/2014	Completed
	Achieve 10% accuracy of the fiber length distribution measurement relative to referenced standard	Purdue	5/15/2014	On schedule
	Demonstrate a 10% fiber length distribution comparison between the machine purge material between PlastiComp, Magna, and Autodesk that is sufficient in fiber length for plaque and 3D molding that provides a fiber length exceeding 2 mm average.	Team	5/31/2014	On schedule
FY14 Q4	Demonstrate that Purdues fiber orientation process achieves a 10% accuracy of fiber orientation measurement compared to the GM Leeds machine measurements	Purdue	7/15/2014	On schedule
	Complete filling analysis on the 3D part for determining the minimum wall thickness for cavity filling and maximizing the average fiber length to exceed 1-2 mm.	PNNL	9/30/2014	On schedule

*Need of studying molding conditions for in-line direct injection molding (D-LFT) of plaques

FY15 Project Milestones

Quarter		Milestone Descriptions	Responsibility	Completed by	Status
FY15 Q1		Complete the improvement of the 3-D ASMI solver and demonstrate a fiber orientation prediction within 15% of measured fiber orientation distributions for the LCF/PP and LCF/PA66 plaque moldings.	Autodesk	10/30/2014	In progress
	Go/no-go	Validate the ASMI predictions for the injection molding of long-carbon-fiber/PP and long-carbon-fiber/PA6,6 center and edge gated plaques using the available ASMI version for mid-plane modeling to achieve a 15% agreement with the experimental fiber orientation and length results.	PNNL	10/31/2014	In Progress
		Complete the implementation of the reduced-order fiber length model in ASMI and demonstrate accuracy equivalent to the full model while decreasing the memory required for fiber length calculation by at least 70%	Autodesk	10/30/2014	In progress
FY15 Q2		Deliver 100 complex 3-D parts with and without ribs per the test matrix to PNNL and finalize the test matrix for fiber length and fiber orientation to validate the complex 3D ASMI models	Toyota/Magna/ PlastiComp	1/15/2015	Not started
FY15 Q3		Purdue to complete and report on the fiber length distribution and fiber orientation for 50wt% LCF/PP and LCF/PA66 3-D parts.	Purdue	4/15/2015	Not started
		Validate predictive results from the ASMI model on the complex 3-D part for fiber orientation and length distribution at the key locations on the part and compare with the experimental results for an accuracy within 15%.	PNNL	6/30/2015	Not started
FY15 Q4		Validate weight and cost reduction study for the complex part by comparative analyses of similar parts in steel and long-glass-fiber/PA66 that demonstrates progress towards achieving 35% weight reduction	Toyota	8/5/2015	Not started

Approach/Strategy

- Build on the past predictive engineering (PE) efforts to integrate, optimize, and validate the PE tools for injection-molded long-carbon-fiber thermoplastic composite structures

  - Improve the ASMI solver for 3D modeling to more accurately predict fiber orientation using 3D models for complex geometry structures
  - Implement the reduced-order length model in ASMI for computational efficiency
  - Perform process modeling of injection-molded LCF/PP and LCF/PA66 plaques and Toyota's complex and proprietary 3D automotive structure using the improved ASMI version
  - Validate the ASMI fiber orientation and length predictions for plaques and the complex 3D structure at selected locations within 15% of the experimental results
  - The improved and validated ASMI package will be used in the design of the complex 3D structure to meet the weight- and cost-reduction targets. Weight and cost reduction study will be based on stiffness criterion and comparative analyses with similar parts in steels and in glass-fiber/PA66

- Address all 3 barriers listed by increasing scientific knowledge of the molding behavior of carbon fibers and enhancing predictive tools

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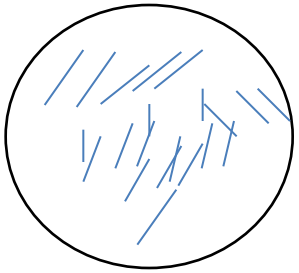
Approach/Strategy (cont.)

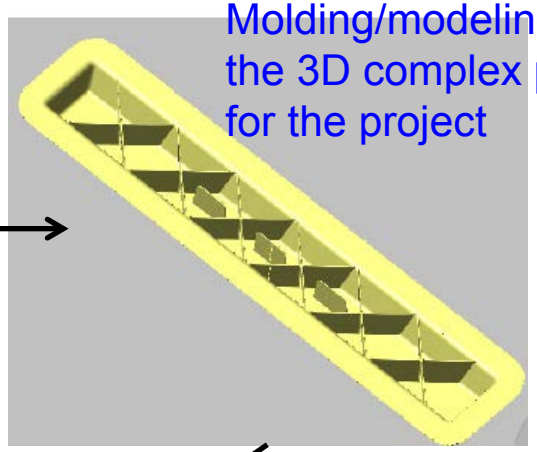
- From LFT compounding to a complex 3D automotive structure injection-molded using long-carbon-fiber thermoplastic compounds

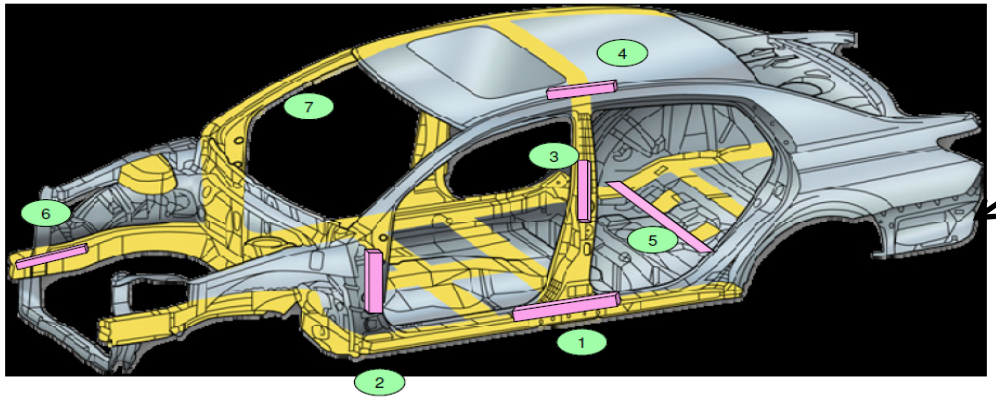
Compounding

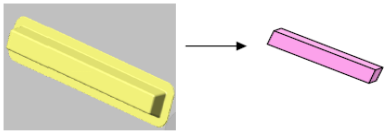


Molding and modeling
LCF/PP & LCF/PA66 plaques

Molding/modeling/design
the 3D complex part
for the project







The proposed component is shown in vehicle

Candidate part can be used at many locations in automobile as shown in the picture above

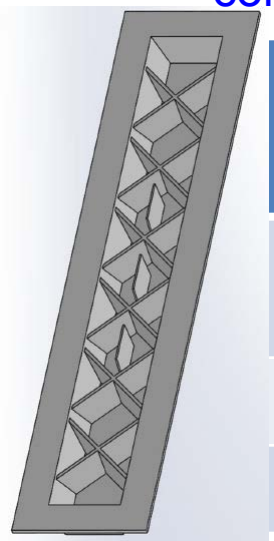
1) Rocker to B pillar reinforcement
2) A pillar reinforcement
3) B pillar reinforcement
4) Roof rain reinforcement
5) Cross member
6) Front rail reinfoecement
7) Interior pillar

Technical Accomplishments

- After hosting the project kick-off meeting, PlastiComp:
  - Successfully compounded and shipped CF/PP and CF/PA66 compounds to Autodesk for rheological and mechanical tests
  - Injection-molded center-gated and edge-fan-gated 7" x 7" x 1/8" plaques under stipulated processing conditions
  - Conducted ASMI analysis of the 3D complex automotive part to advise the team on moldability of the part vis-a-vis sectional thicknesses
  - In continuing dialogue with Magna on optimized LFT injection-molding parameters and equipment

High injection speed produced warpage of an LCF/PP plaque

Injection molding pre-analysis of the 3D complex part to estimate part moldability



WALL THICKNESS (mm)	INJECTION PRESSURE (Ksi)	REMARKS
2	11	Harsh on fiber-length retention
3	5.5	Borderline
3.5	4.3	Acceptable

Technical Accomplishments (cont.)

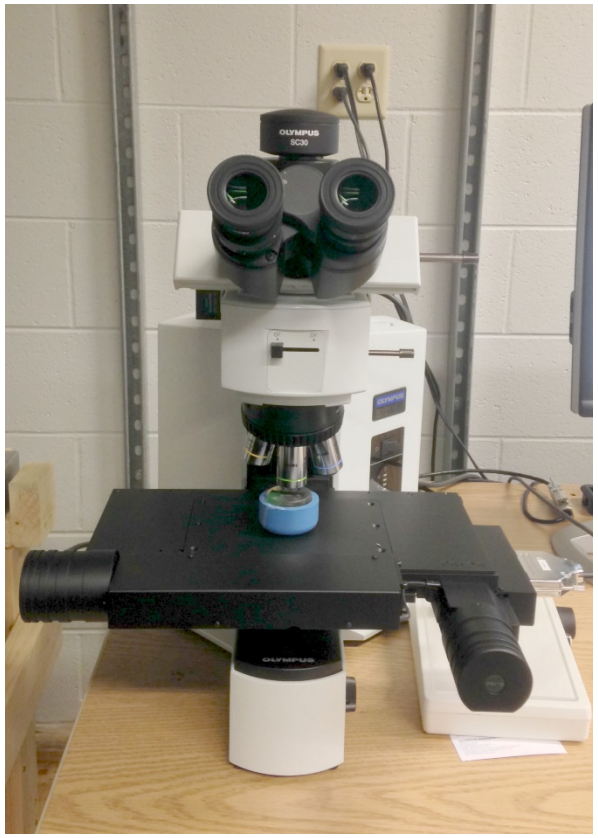
- Summary of compounds and injection speeds achieved by PlastiComp

Weight Fraction	Materials	Processing	Condition	Number of edge-gated plaques	Number of center-gated plaques
30%	CF/PP	LFT	Slow	10	10
			Fast	10	10
	CF/PA6,6	LFT	Slow	10	10
			Fast	10	10
50%	CF/PP	LFT	Slow	10	10
			Fast	10	10
	CF/PA6,6	LFT	Slow	10	10
			Fast	10	10

Additionally, purge materials from the injection nozzle at various prescribed injection speeds for the above-listed compounds were also sent to program partners for fiber-length attrition analysis

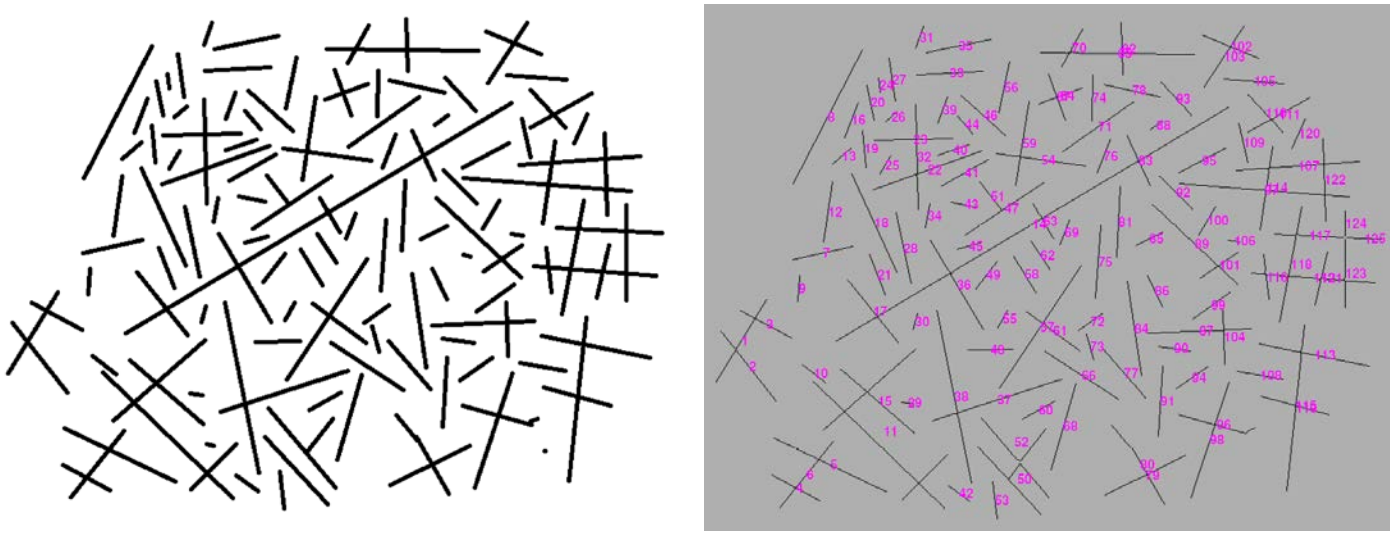
Technical Accomplishments (cont.)

- Fiber orientation measurement method (Purdue University)
  - Deployed Optical Microscope with motorized stage
    - OLYMPUS BX51M optical microscope with a motorized system was obtained and setup.
    - Available magnifications: 5x, 10x, 20x, 50x, 100x.
    - Motorized stage in conjunction with OLYMPUS Stream software allows for automated stitching with high magnifications.
    - High Dynamic Range (HDR) and Extended Focus Image (EFI) allow to create image with high contrast and in focus even with varying heights.
    - Replaces the need to use the Leeds instrument



Technical Accomplishments (cont.)

- Fiber length measurement software (Purdue University)
  - Fiber length measurement software written using MATLAB®.
  - Allows for automated measurement of fiber length distribution from image obtained from microscope.
  - Capable of distinguishing fibers crossing over each other, measuring individual lengths, and giving fiber length distributions.
  - Enhances Purdue's work flow and throughput for fiber length measurements.

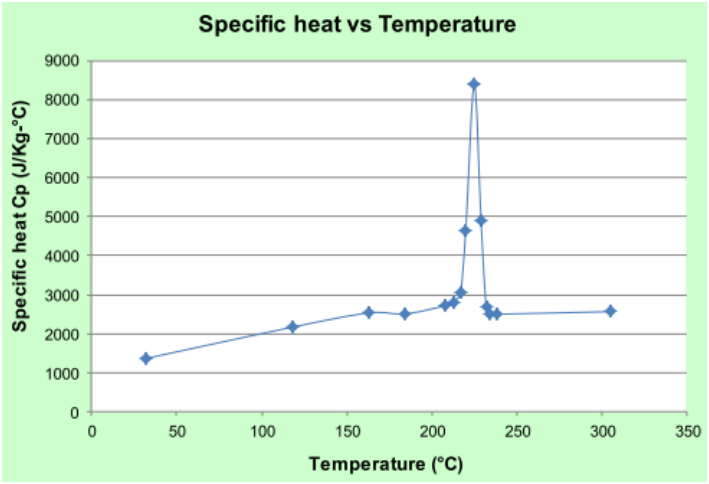


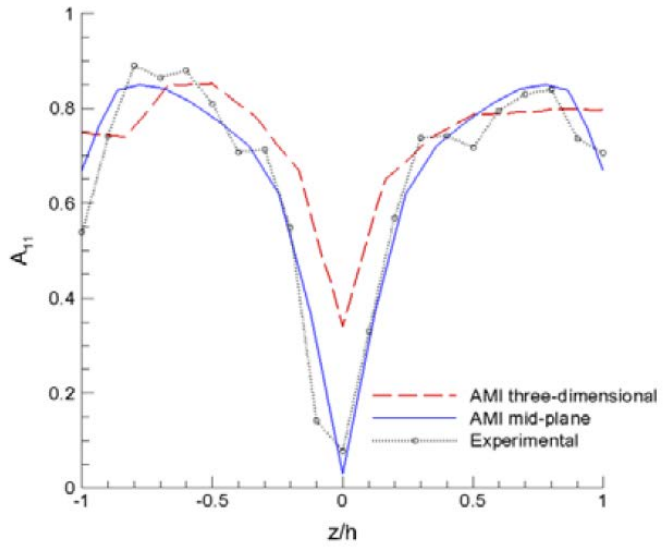
Automated identification and labeling of a sample image with multiple fiber crossings

Technical Accomplishments (cont.)

AUTODESK.

- Material Characterization of four LCF compounds (Autodesk)
  - Viscosity, Thermal Properties, Mechanical Properties, PVT / Density
  - Material data files already distributed to all project participants
- Commenced 3D RSC fiber orientation model improvements (Autodesk with Univ. Illinois consultant services)
  - Focussing on improving orientation predictions in the core region
  - Found reasons for differences between 3D predictions and experiments
  - Improvements still in progress





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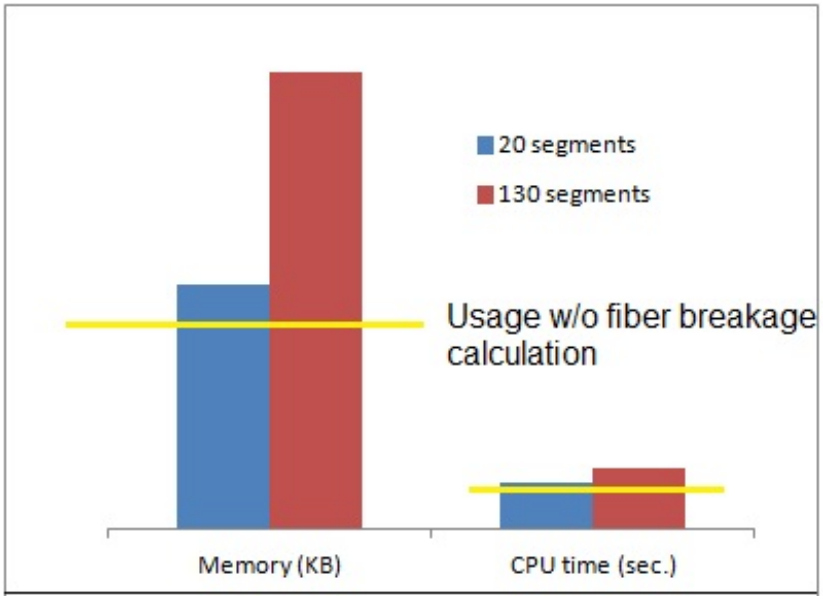
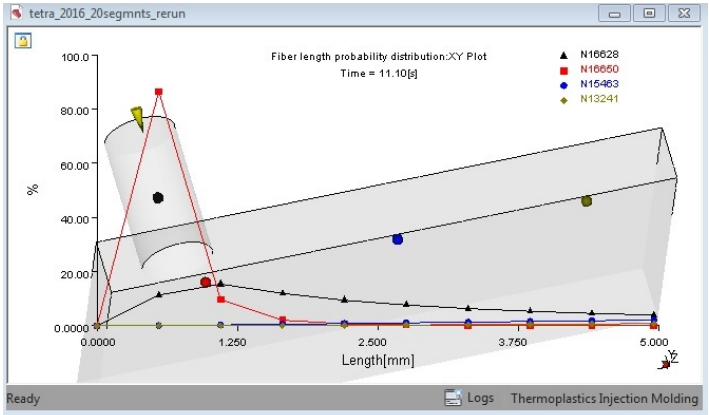
Technical Accomplishments (cont.)

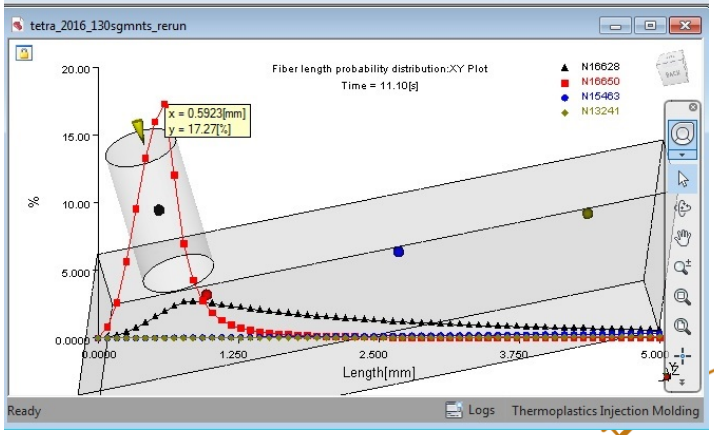
- Commenced work on reduced order model (ROM) for fiber length prediction

AUTODESK.

  - Received consultant services from Prof. CL Tucker III (Univ. Illinois)
  - The ROM using proper orthogonal decomposition (POD) has been implemented in a prototype code
  - Assessment of accuracy with different length segments and establish a baseline for memory and CPU usage:



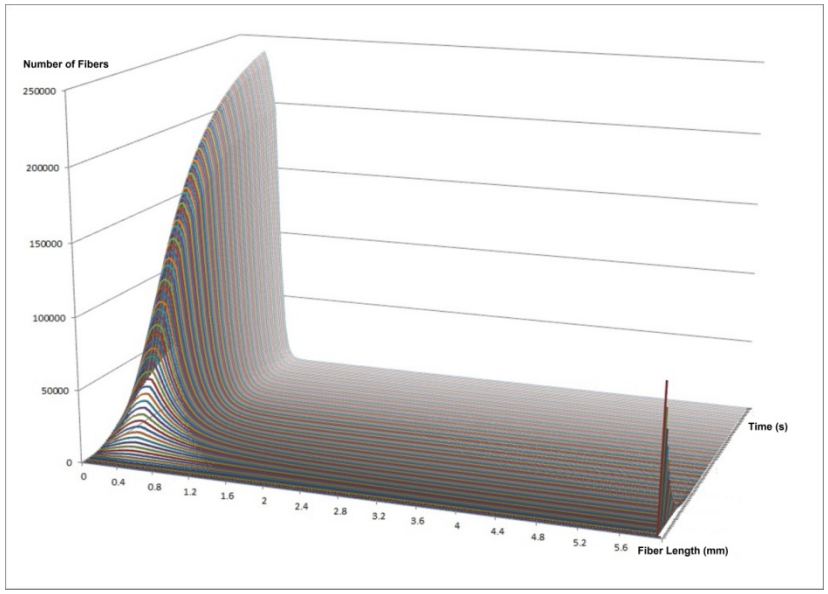




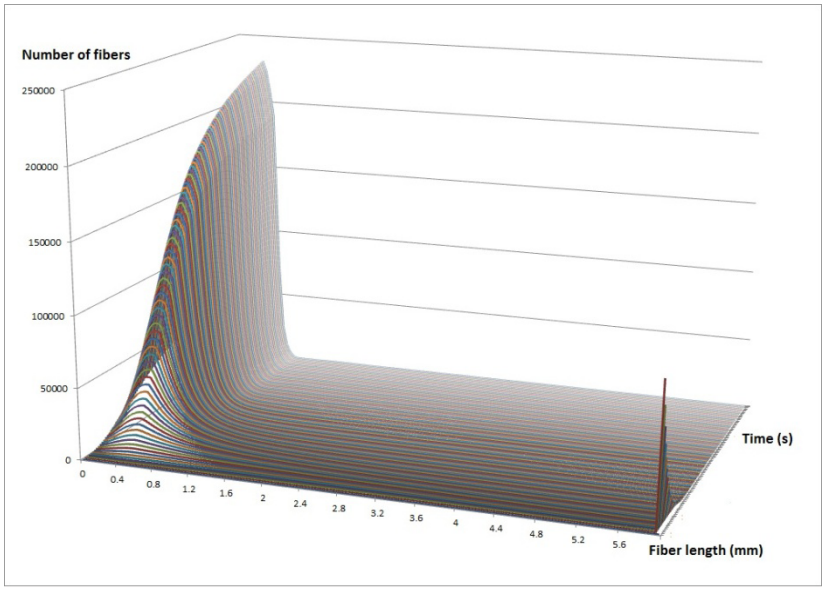
Left: Memory and CPU required for 20 and 130 segments.
Yellow lines represent the memory / CPU usage without fiber breakage calculation
Right: Accuracy comparison between 20 (top) and 130 (bottom) segments

Technical Accomplishments (cont.)

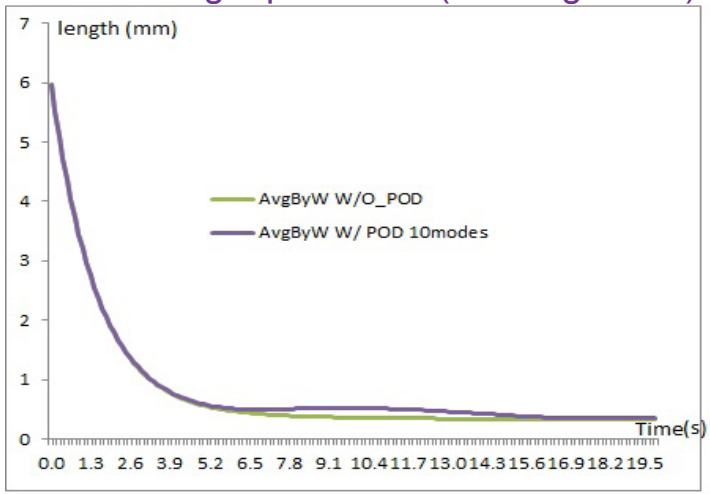
- Assessment of accuracy of ROM with POD
  - ROM is to reduce the memory usage with acceptable errors



Baseline length prediction (150 segments)



ROM prediction of fiber length with 10-mode POD

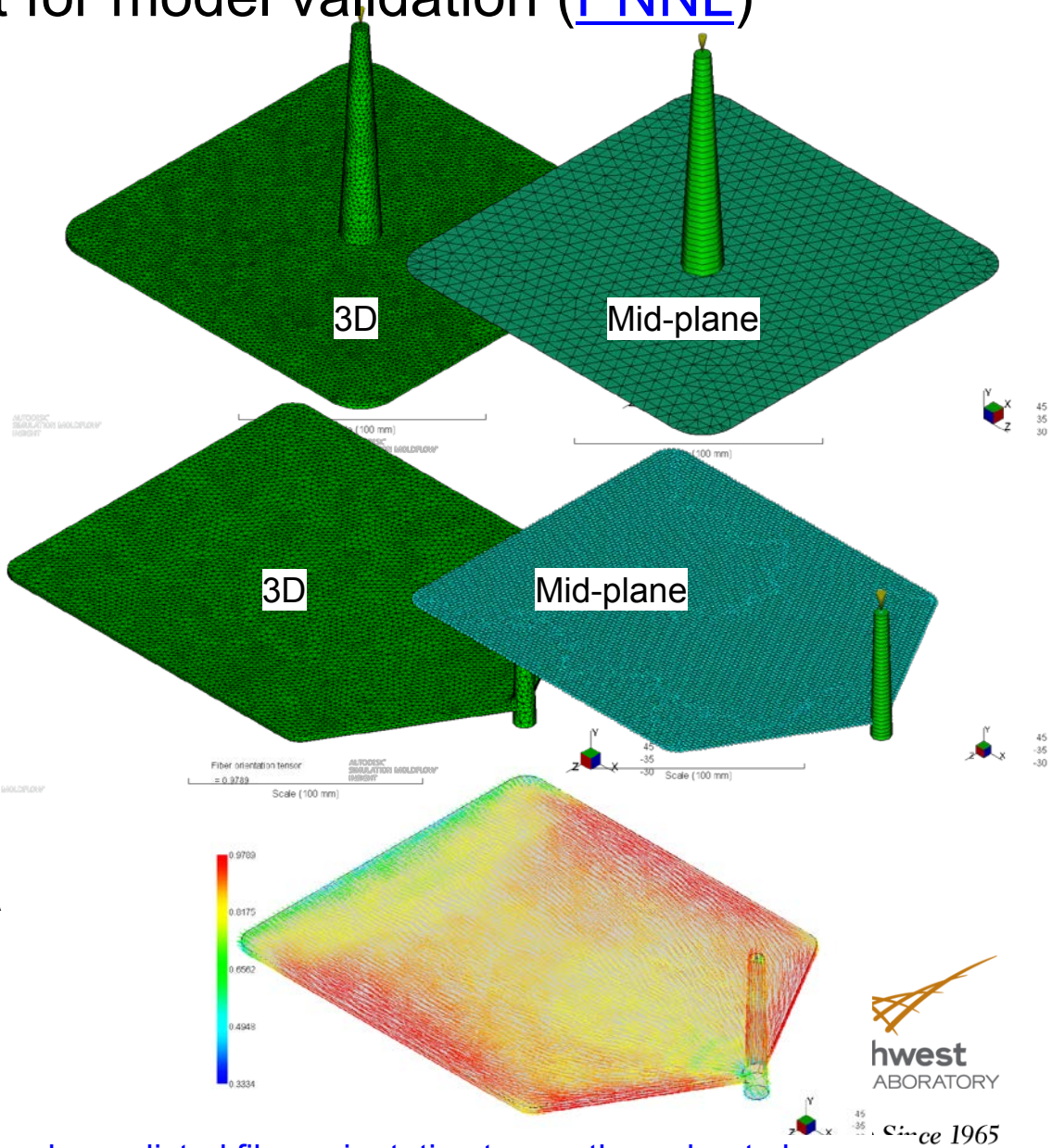


Shown here is a 15:1 memory reduction rate

The errors by 10-mode POD compared to baseline in the curve of fiber length averaged by weight

Technical Accomplishments (cont.)

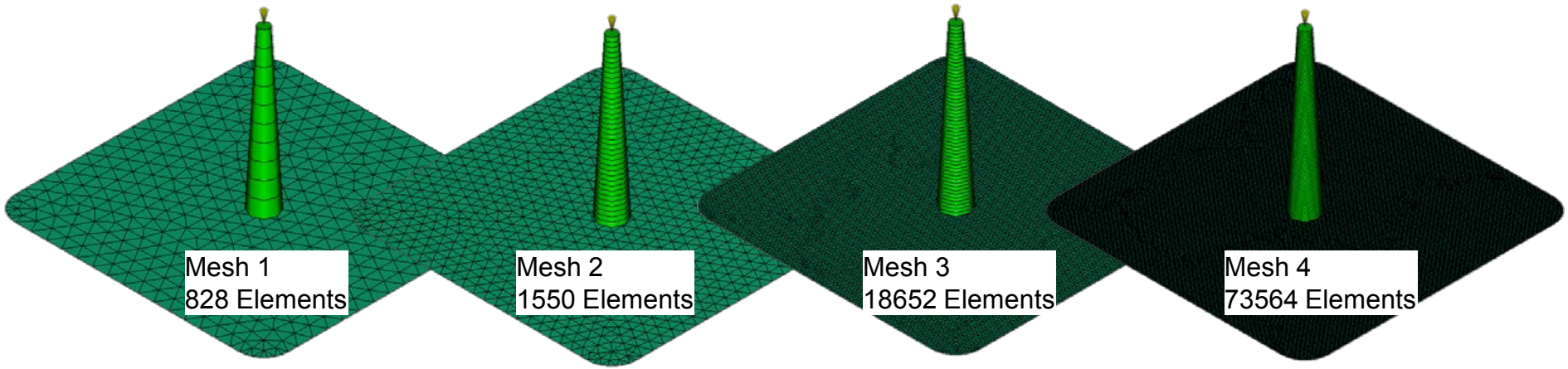
- ASMI models were built for model validation (PNNL)
  - Process parameters from actual moldings by PlastiComp
  - Material (i.e., rheological) data from Autodesk pellet characterization results
  - Created center-gated and edge-gated models with both mid-plane and 3D meshes
  - Ran preliminary models but will need to update them for the model parameters identified from actual moldings data when available



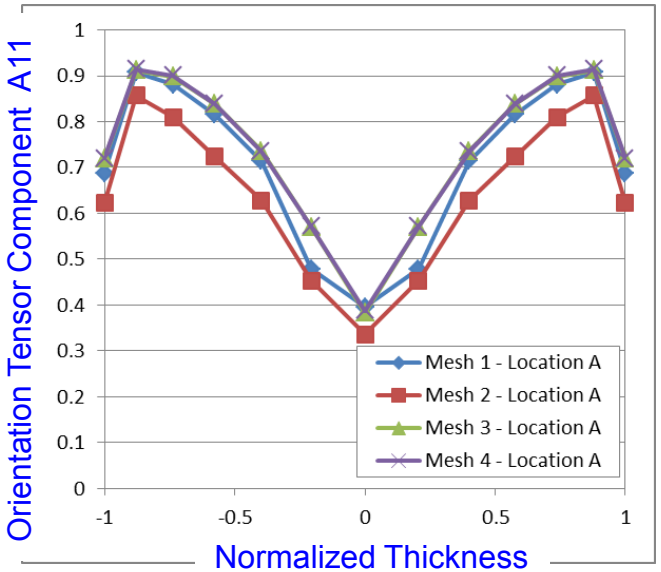
Example predicted fiber orientation tensor throughout plaque

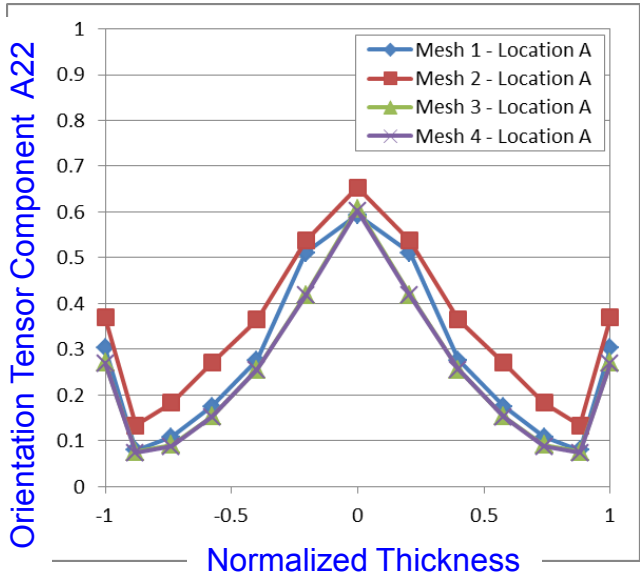
Technical Accomplishments (cont.)

- ASMI mesh sensitivity analysis (PNNL)
  - Fiber orientation results were compared for 4 different mid-plane meshes using the ASMI mid-plane models for the 30 wt% CF/PP plaque



- Predicted fiber orientations are all close.
- Convergence in results is observed with finer meshes.





Remaining Challenge and Barriers

- Risk of not achieving required 3D fiber orientation accuracy
- Risk of much longer CPU time for the reduced order length model with the proper orthogonal decomposition (POD) method
- Risk in selection of the POD modes
- Challenge in formalizing a batch process to separate the individual fibers to measure length while not biasing the results
- Challenge in in-line direct injection molding of long-carbon-fiber thermoplastics (D-LFT) for high concentrations of carbon fibers (~50 wt% and higher)

Proposed Future Work

- For the rest of FY14
  - Purdue to apply automated fiber length measurement technique to pellets to achieve 10% accuracy of the FLD measurement relative to standards
  - Purdue to compare in-house fiber orientation measurement method to the Leeds instrument to achieve 10% accuracy for measurements between the processes
  - Purdue to apply developed fiber length and orientation measurement methods to measure fiber length and orientation distributions for PlastiComp's plaques
  - PlastiComp to mold 30wt% and ~50wt% CF/PP and CF/PA66 plaques using the existing in-line direct injection molding process (D-LFT)
  - PNNL to pre-analyze the complex 3D part using actual rheological data to guide part molding
- For FY15
  - Autodesk to complete 3D ASMI solver improvements for fiber orientation
  - Autodesk to complete implementation of the ROM for fiber length in ASMI
  - PNNL to validate ASMI predictions for fiber orientation and length distributions in PlastiComp plaques within 15% of the experimental data
  - Magna to mold the Toyota complex 3D part with PlastiComp's assistance
  - Purdue to complete fiber orientation and length measurements for the 3D part
  - PNNL to validate ASMI predictions for fiber orientation and length distributions in the 3D part within 15% of the experimental data
  - Toyota and PNNL to perform weight and cost savings for the 3D part

Summary

- Relevance
  - Integrate, optimize, and validate the predictive engineering tools for injection-molded long-carbon-fiber thermoplastic composites for automotive applications towards achieving weight and cost reductions
- Approach
  - Improve ASMI packages to accurately and efficiently predict fiber orientation and length distributions in 3D LCF thermoplastic structures
  - Perform injection molding of plaques to understand molding LCF thermoplastics under different filling conditions→ mold the complex part
  - Build and apply measurement methods for fiber orientation and length distributions to obtain data for model validation
  - Validate improved ASMI tool for LCF plaques and the complex 3D part → perform weight and cost savings for the part
- Technical Accomplishments
  - Molded 30 wt% and 50 wt% LCF/PP and LCF/PA66 plaques
  - Established methods for fiber orientation and length measurements
  - Completed material characterization for 4 LCF/PP and LCF/PA66 compounds
- Future work
  - Continue model improvements/implementation in ASMI
  - Validate improved ASMI predictions against the measured data
  - 3D complex part study: molding, model validation, and weight/cost reduction