Development of Tailored Fiber Placement, Multi-functional, High-Performance Composite Material Systems for High Volume Manufacture of Structural Battery Enclosure

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General Motors
2021 Annual Merit Review
June 22, 2021

Project ID: MAT198

Overview

Timeline

- Project Start Date: April 1, 2021#
- Project End Date: June 30, 2024
- Percent Complete: 2%

Budget

- Total project funding
  - Total : $10,330,000
  - DOE Share: $7,500,000
  - Contractor Share: $2,830,000
- Funding for FY21:
  - Total: $1,149,000
  - DOE share: $834,174
  - Contractor share: $314,826

#requested DOE a new timeline for the project due to late start

Barriers and Technical Targets

Barriers addressed*

A. ***Material systems development :*** Structural composite material system having multi-functional capabilities such as hybrid fibers (ex. carbon and glass), self-health monitoring, fire-retardance, and electro-magnetic compatibility (EMC) to make a positive business case (cost increase per pound saved is less than $5)

B. ***Predictive technology development:*** Modeling tools to predict the performance of manufacturing process and structural design within 15% of experimental results. AI/ML technology development for process monitoring to save costs of inspection and scrap during manufacturing.

C. ***Demonstration:*** Using the developed material systems, design, build, and test a structural composite battery enclosure, and compare the weight, performance metrics with that of a baseline metallic assembly.

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

Participants

General Motors
Coats
Columbia University
Continental Structural Plastics (CSP)
ESI Group, NA
Michigan State University
University of Southern California

Relevance

High Performance Multi-functional Composite Material Systems

- Hybrid carbon and glass fibers in various architectures for cost-effective business case (≥ 25 Msi, strain ≥ 1%)
- Self-health monitoring electronic circuits embedded in the composite for value proposition
- Integrated fire-retardant material systems for use in the future design of components for the battery enclosures
- Electro-magnetic compatibility for value proposition and use for the future design of battery enclosures
- High-pressure resin transfer molding (HP-RTM) for volume manufacturing needed for automotive industry
- Predictive computational tools for virtual design and eliminating cost of trial-and-error iterations
- AI/ML technologies for process monitoring and component design
- Reduce the lead time and costs to accelerate the implementation of structural automotive composites.
- Enable the usage of composites for significant light-weighting of automobiles and thus improve fuel economy/range, and lower emissions (reduce greenhouse gas emissions).

Cost Barrier

- Will demonstrate the ability to manufacture the automotive composite assembly at no more than **$5 per pound saved (2010 dollars)**.

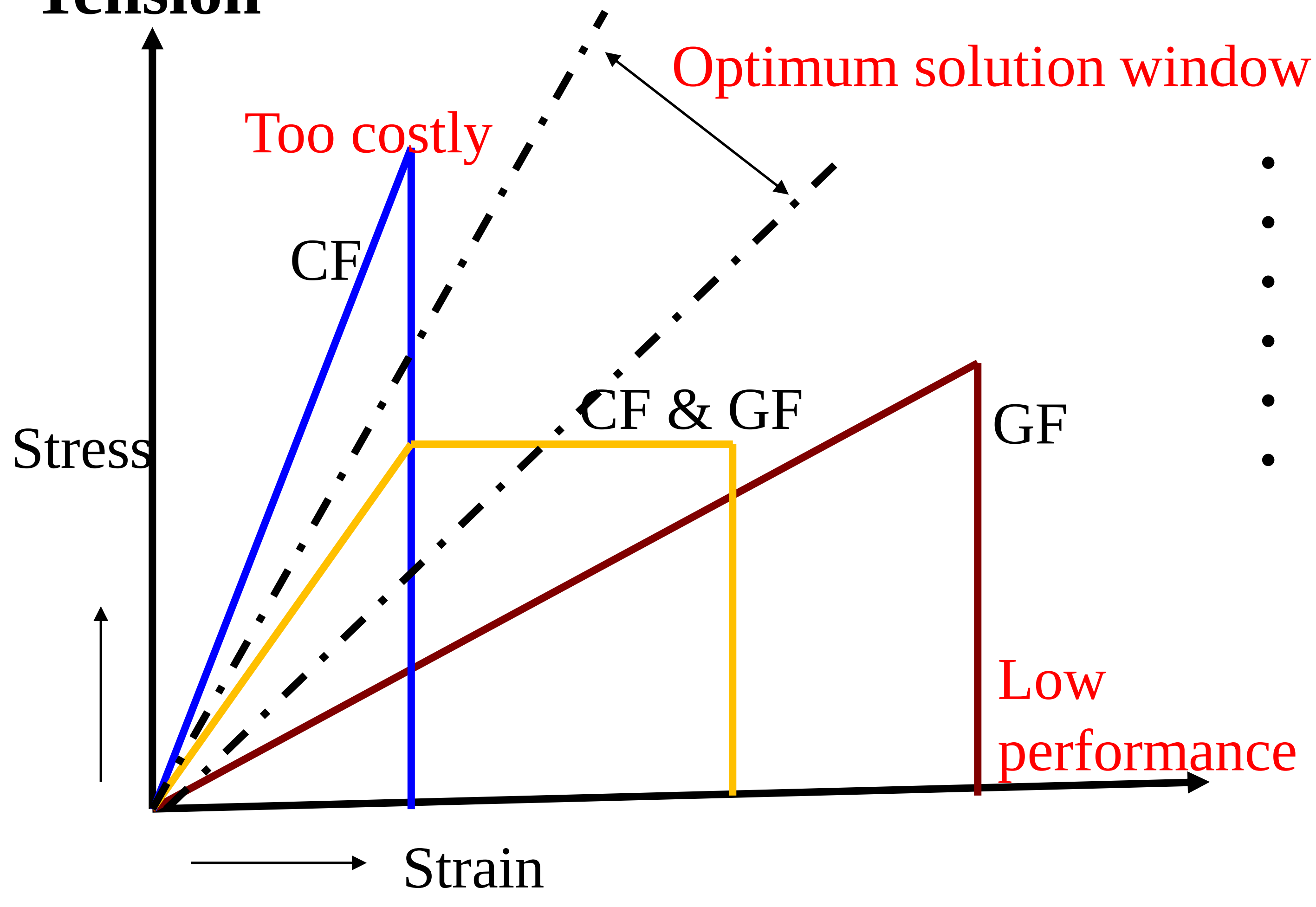
Performance Barrier

- Will demonstrate the viability of composite materials to meet vehicle performance requirements while reducing vehicle assembly weight **by 25%** compared to a current steel structural battery enclosure. The cycle time to manufacture the composite panels need to be less than 3 minutes.

Relevance

Hybrid Fiber Composites

Tension



- CF is >10 times costly than GF
- Strength ratio of GF*/CF$ = 3448/4157 = 0.83
- Stiffness ratio of GF*/CF$ = 72.4/242 = 0.30
- Load case interest – strength based
- Domain of interest – beyond the initial failure
- A flexure, crashworthiness performance case will be interesting with more glass fiber content as glass fibers when compared to carbon fibers has good strength properties compared to stiffness.

*E-glass
$PX35 Zoltek

Relevance

Steps in implementing CF in Automobiles

Current

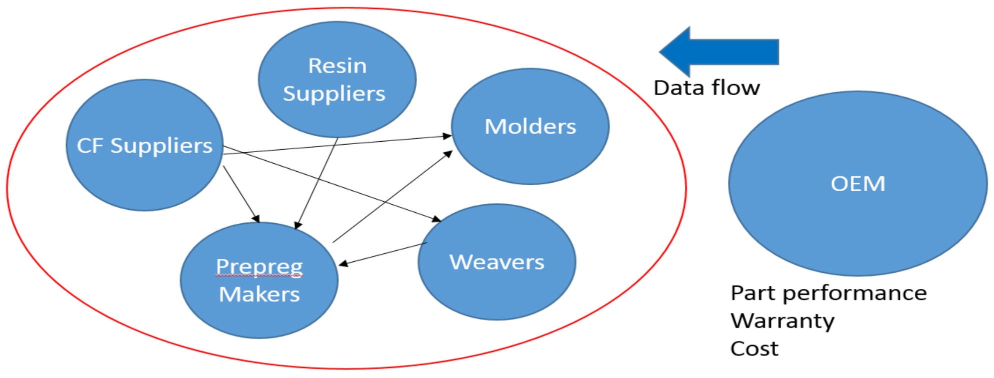
- Design.
- Selection of manufacturing process.
- Manufacturing feasibility.
- Prototype build and learn.
- Modify design and manufacturing process, if needed.
- Improve prototype build and make parts.
- Extrapolate to high volume manufacturing.
- Build the part in high volume, iterate to get good quality.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

Future

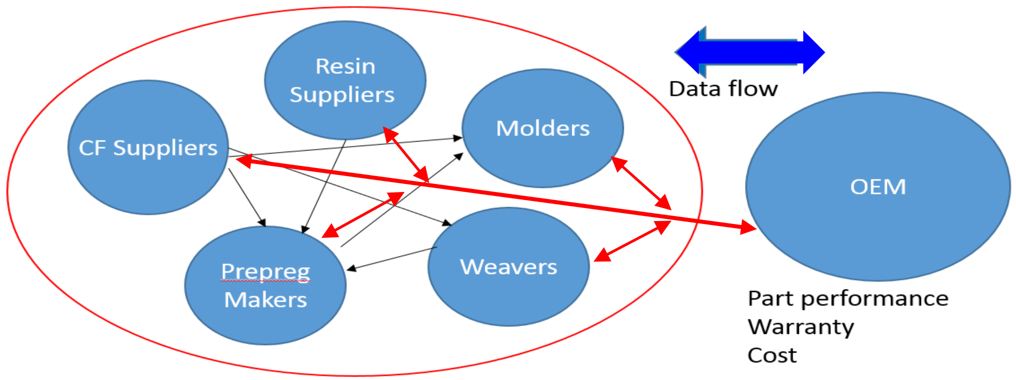
- Design.
- Virtual manufacturing simulation and improve the design for optimizing the cost.
- Include manufacturing outcome in performance simulation and further optimize the design to meet the requirements.
- Build tools, manufacture parts and check the performance

Workflow between OEM and Suppliers

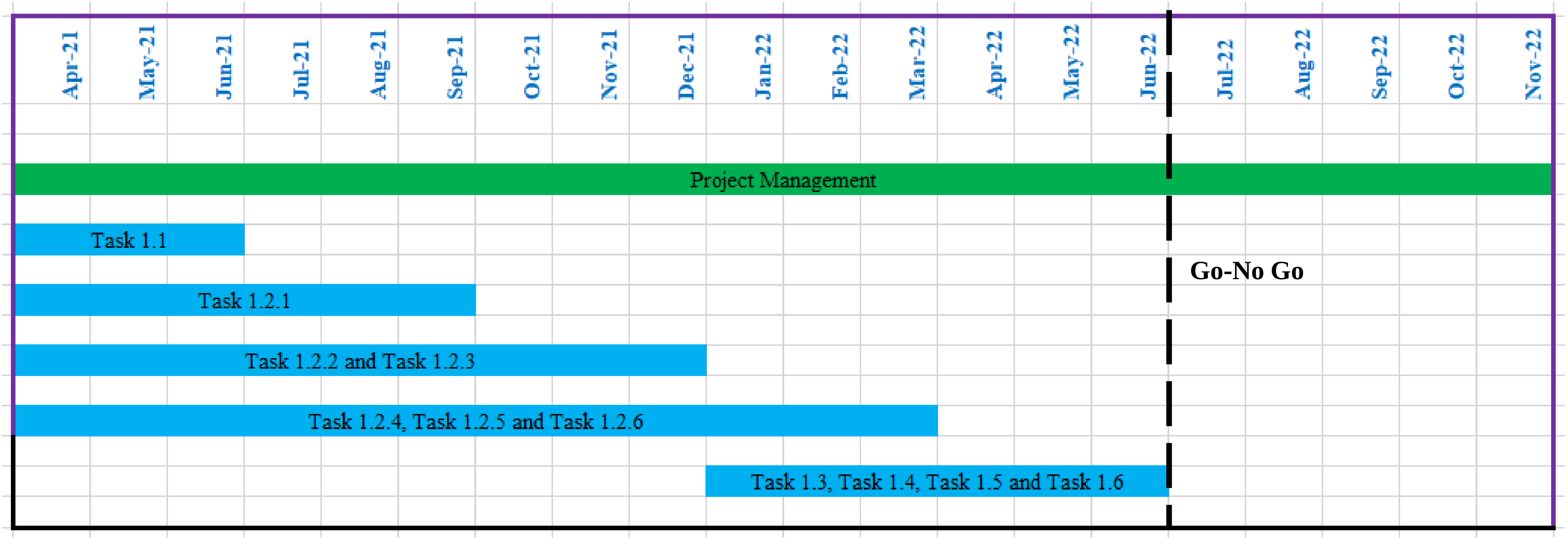
Current



Future



Milestones



Task	Details
Task 1.1	Determine functional requirements of baseline assembly
Task 1.2.1	Evaluate and develop an optimized fiber material systems
Task 1.2.2	Evaluate and develop required manufacturing model
Task 1.2.3	Evaluate and develop required structural model
Task 1.2.4	Evaluate and develop required self-health monitoring technologies
Task 1.2.5	Evaluate and develop AI/ML technologies for monitoring the manufacturing process
Task 1.2.6	Evaluate and develop cost models

Task	Details
Task 1.3	Initial structural design of battery enclosure
Task 1.4	Initial manufacturing design of battery enclosure
Task 1.5	Initial self-health monitoring technology implementation
Task 1.6	Initial AI/ML technology implementation

Go- No Go - Model error less than 15%

Approach/Strategy

- Hybrid fiber material system to lower the material costs – utilize the ductility improvement cited in the recent literature
- Optimum hybrid fiber ratio (carbon and glass) to maximize the performance for a given cost
- Engineer the microstructure (spacing of fiber bundles, stitch density) of the fiber preform to optimize the performance such as draping, injection (enhanced permeability)
- Multi-functional material systems including fire-retardance and EMC performance
- Develop the technology for high-pressure resin transfer molding (HP-RTM) process
- Develop the technology for self-health monitoring
- Develop the AI/ML technology for process monitoring
- Predictive modeling tools for the developed material systems for both manufacturing and structural performance
- Demonstrate the technology development by design, building, testing and comparing the performance metrics (weight, cost, performance) with that of a baseline metallic assembly.

Accomplishments

FY 21 Accomplishments

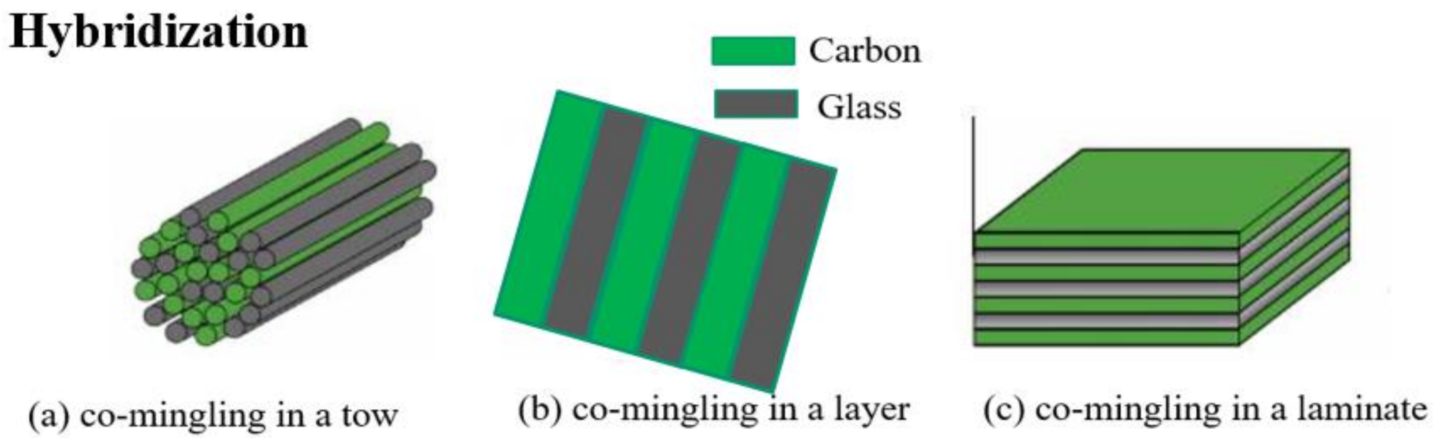
- Determined the functional requirements of the baseline metallic assembly (Task 1.1).
- Finalized the design of experiments test matrix (full factorial) for determining the optimum hybrid material system for performance, draping, injection and structural performance. The same data will be used to develop predictive models.
- Finalized test matrix for the characterization of conductive wiring for developing the self-health monitoring technology.
- Developed a demonstration problem for the AI/ML process monitoring technology.

Accomplishments

Baseline Model, functional requirements of the battery enclosure

- Steel based design for the battery enclosures
- Performance requirements
  - Mass, cost, etc.
  - Intrusion of the battery tray during critical load case of side pole impact
  - These parameters will be used to design the future composite battery enclosure assembly

Accomplishments



Test matrix for material development

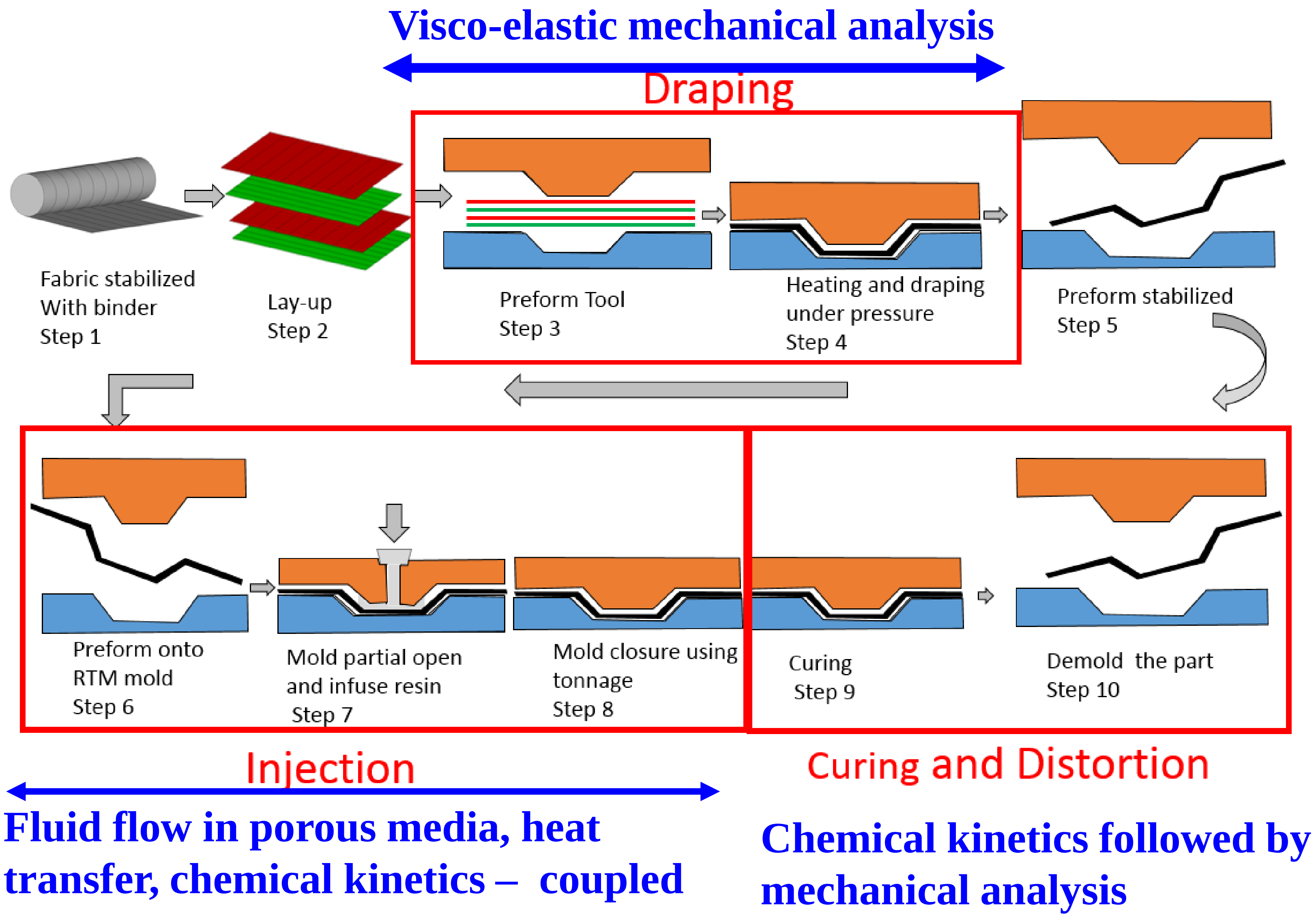
Variables	Factor 1	Factor 2	Factor3	Factor 4	Total Factors
Layup	(0/45/-45/90/90/-45/45/0)				
CF/GF ratio	60%	45%	20%		3
Thermoplastic Fiber	0	10%			2
Co-mingling type	In-fiber tow	Lamina	Laminate-1	Laminate -2	4
Stitch material	Thermoplastic				1
Resin type	Epoxy				1
Replicates					2
Total combinations					48

Lamina	5 CF tow bundles and 5 GF bundles side by side*
Laminate-1	$(0/45/-45/90)_s$ - 0, 90 layers are CF, and 45 and -45 layers are GF
Laminate-2	$(0/45/-45/90)_s$ - 0, 90 layers are GF, and 45 and -45 layers are CF

*Specimen width = 25 mm

Manufacturing Process & Models

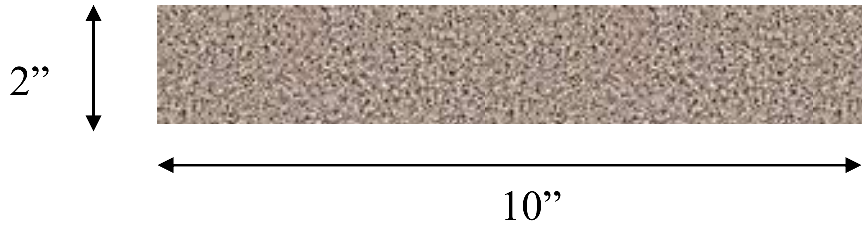
HP-RTM Process - Multi-physics



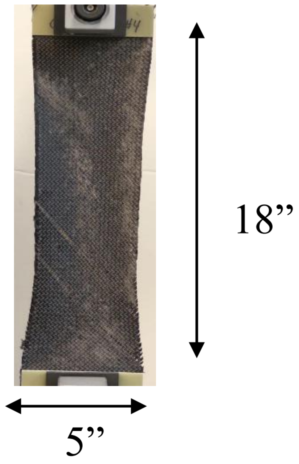
- Draping/Injection/ Curing stages
- Different physical processes need to be modeled for each manufacturing process.
- Output from one process is an input to the next process.

Accomplishments

Testing matrix for draping model development



Bending characterization



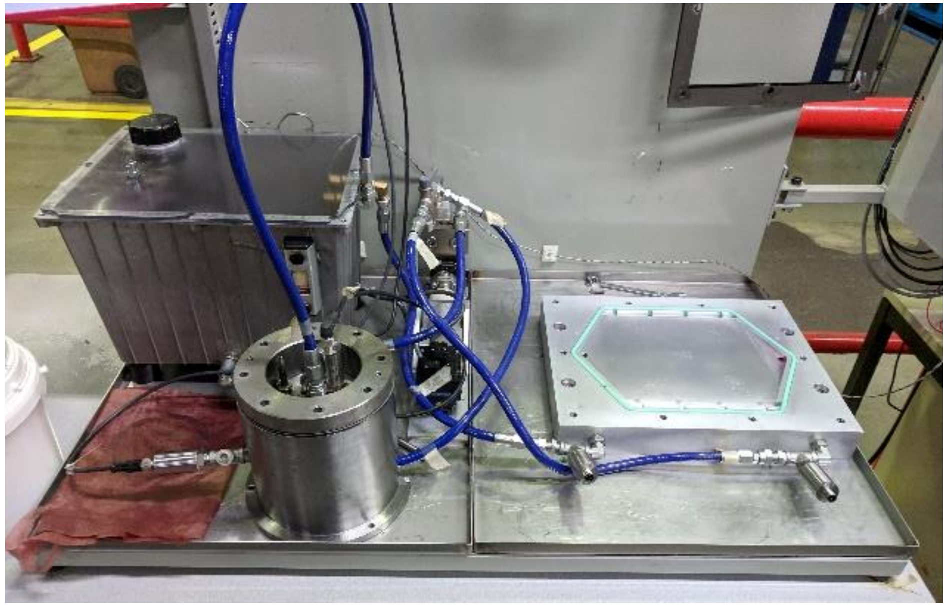
Bias-extension

Dry fabrics needed to test for both the bending and bias-extension experiments

Variables	Factor 1	Factor 2	Factor3	Factor 4	Total Factors
Co-mingling	Tow	Lamina	Laminate		3
Layup	Bias-extension tests - (45/-45/45/-45)				1
	Bending tests - 0/90/90/0 and 90/0/0/90 with 0 deg. along the 10” side				2
Material	GF				1
Spacing of fiber bundles	Standard	Higher			2
Stitch density	Low		High		2
Stitch material	TP				2
Base material	50 gsm. GF		TP		1
Total combinations					48

Accomplishments

Testing matrix for injection model

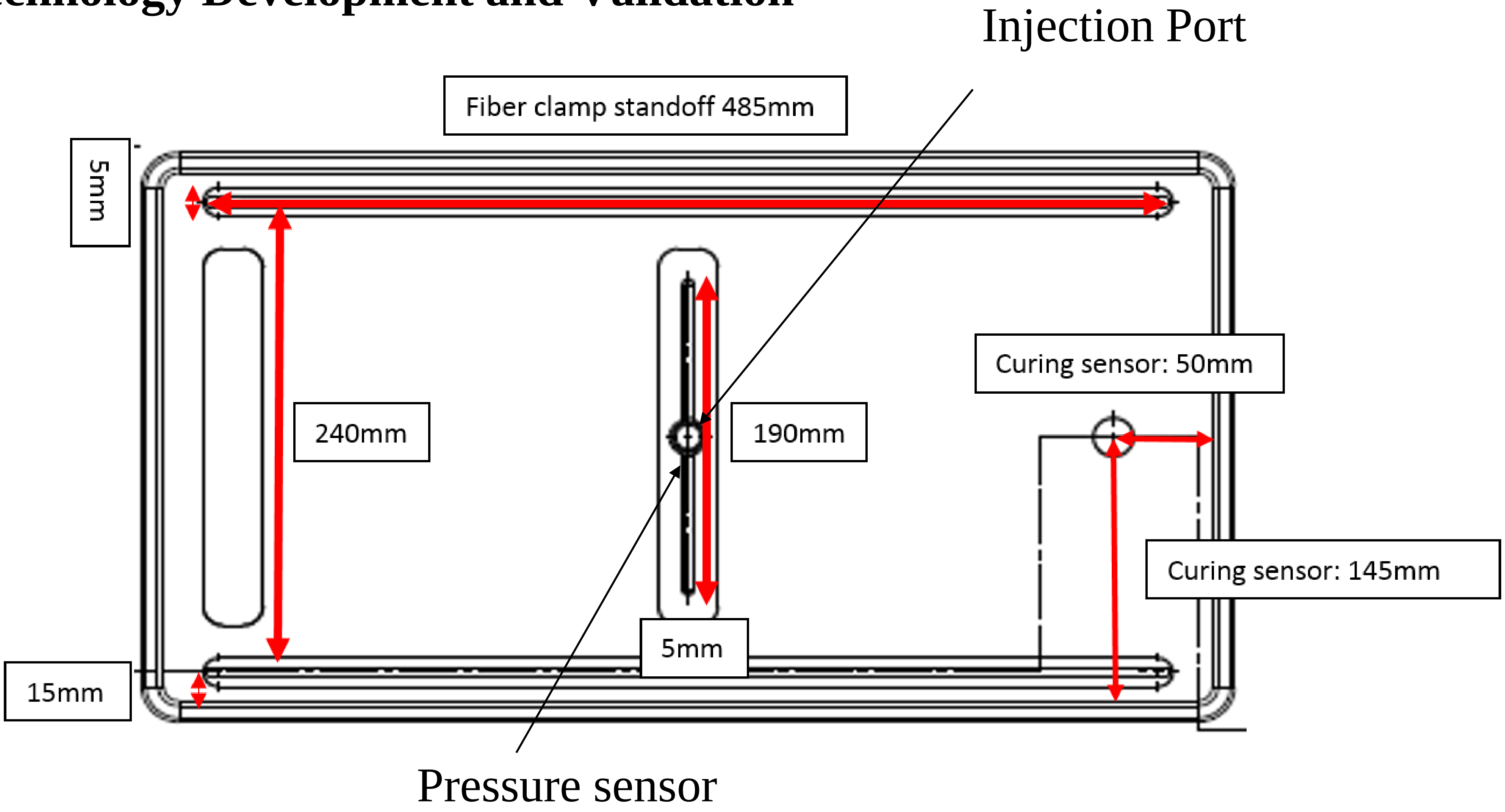


Permeability measuring instrument

Variables	Factor 1	Factor 2	Factor3	Factor 4	Total Factors
Layup	0	45	90		3
CF/GF volume ratio	60%	45%	20%		3
Spacing of fiber bundles	Standard	Higher			2
Stitch density	Low	High			2
Base material	50 gsm. GF				1
Replicates	1				1
Total combinations					36

Accomplishments

AI/ML Technology Development and Validation

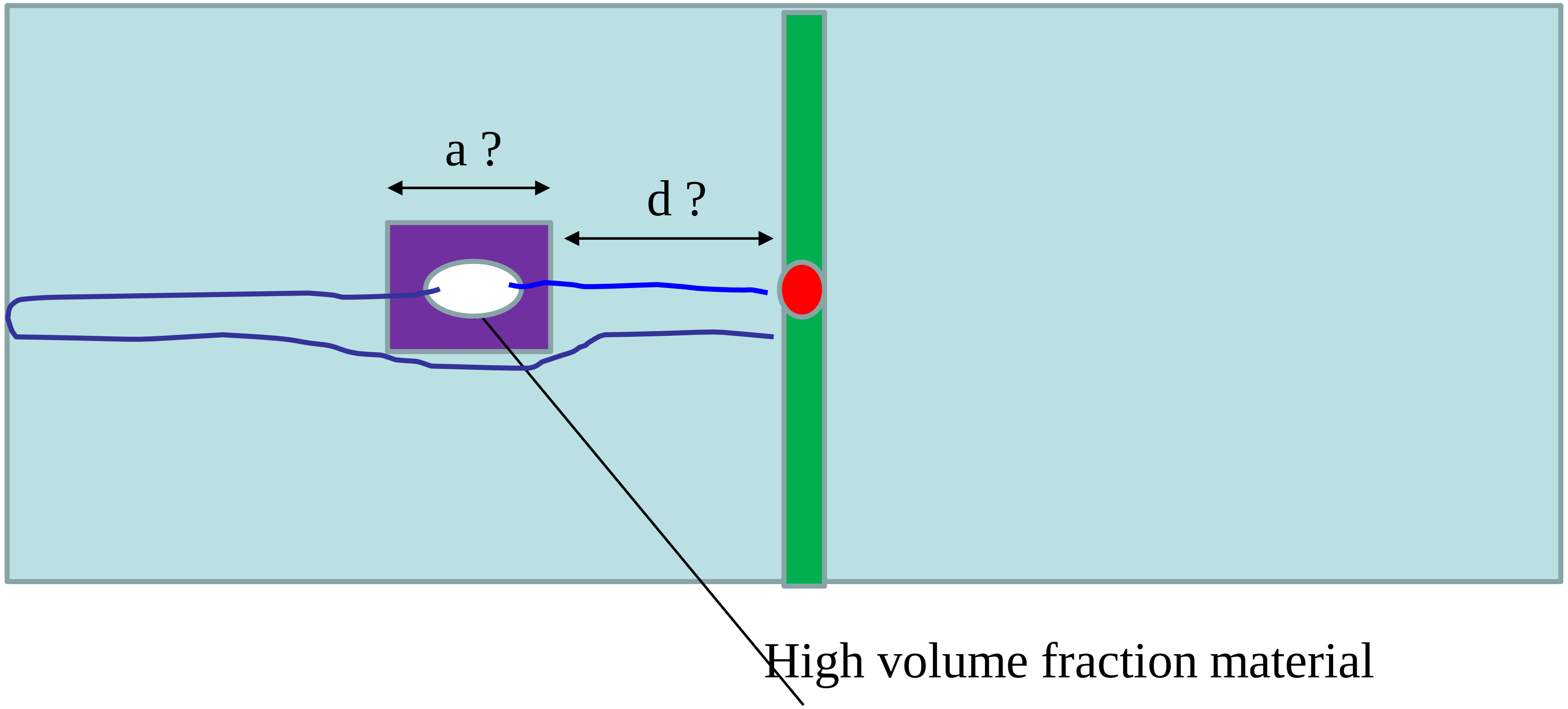


HP-RTM Mold

Accomplishments

AI/ML Technology Development and Validation

Create an intentional dry spot and use AI/ML technology to mitigate/remedy the defect (modifying the process conditions on the fly)

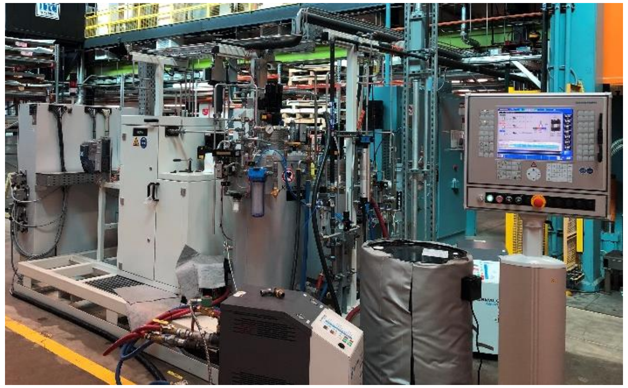


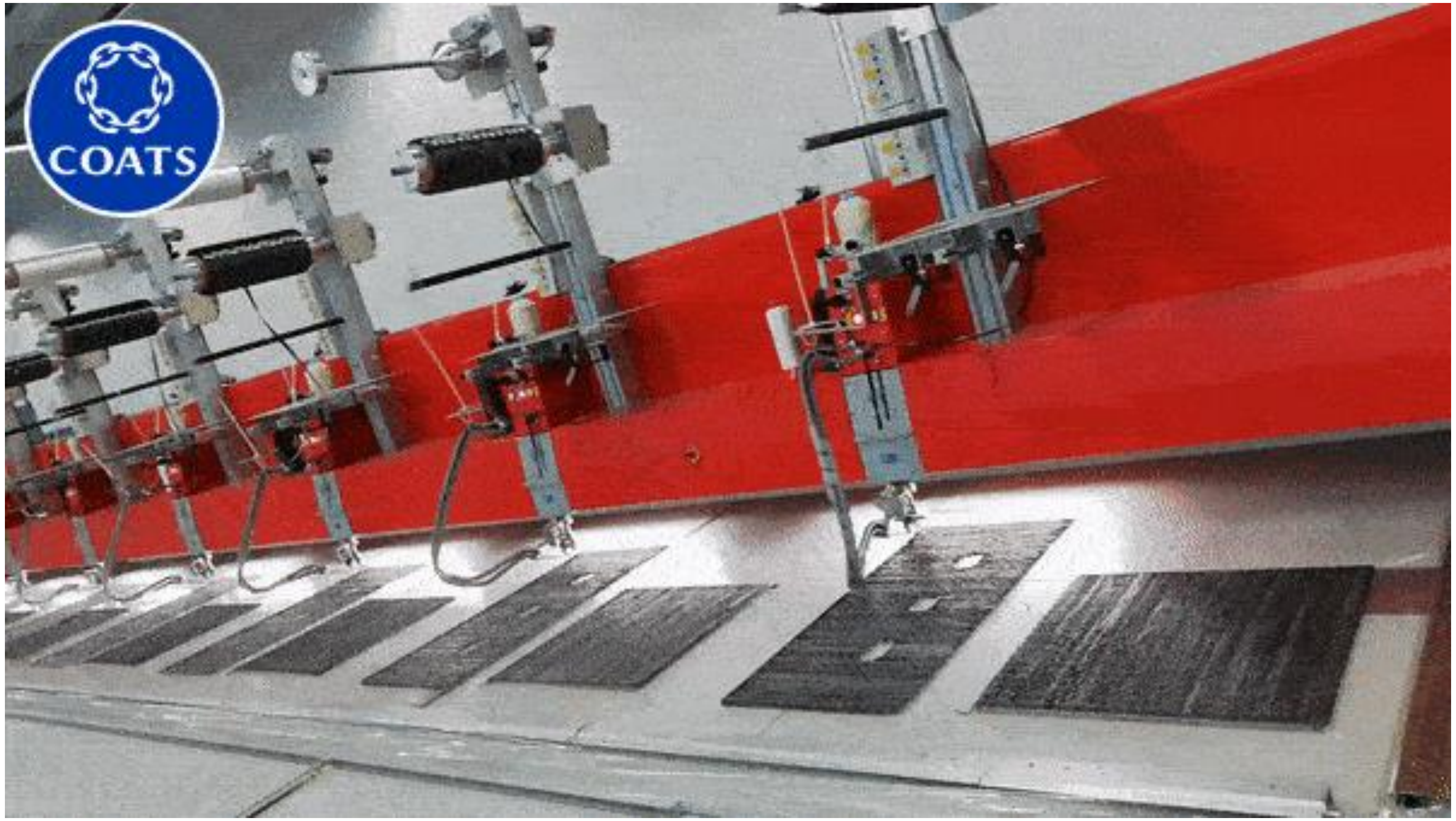
Experimental setup for AI/ML demonstration

Tasks:

1) Determine the location, dimension, and the volume fraction of the obstruction to create a void from simulations
2) Mold the samples to test the condition
3) Develop the AI/ML models that can predict the process conditions to mitigate/eliminate the dry spot following an indication on the pressure sensor reading
4) Validate the developed AI/ML in a demonstration exercise

Unique Facilities





GM HP-RTM System

- 1000T press
- Commercial injection system

Coats – Tailor Fiber Placement Machine

Responses to Previous Year Reviewers' Comments

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

Partners/Collaborators

General Motors

- **Lead – PM**
- Baseline Steel assembly
- Design of composite assembly
- HP-RTM reinforcement
- Structural Design
- Structural testing/ validation

Coats

- Tier 2, technology leader in TFP

Columbia University

- Strong expertise in sensors, energy harvesting technology and data analytics

Continental Structural Plastics

- Key Tier1 supplier
- Process design
- FR material development

ESI

- Virtual prototype software development company, Global technology leader

Michigan State University (IACMI)

- State-of-the-art federally funded facilities for composite manufacturing

University of Southern California

- Expert at AI/ML
- DOE SciDAC institute

Remaining Challenges and Barriers

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

- Finalize structural design of the composite battery enclosure
- Finalize manufacturing process design of the composite assembly
- Finalize AI/ML technology for monitoring the manufacturing process of composite assembly
- Build the manufacturing tools
- Initial manufacturing of components of the assembly

Summary

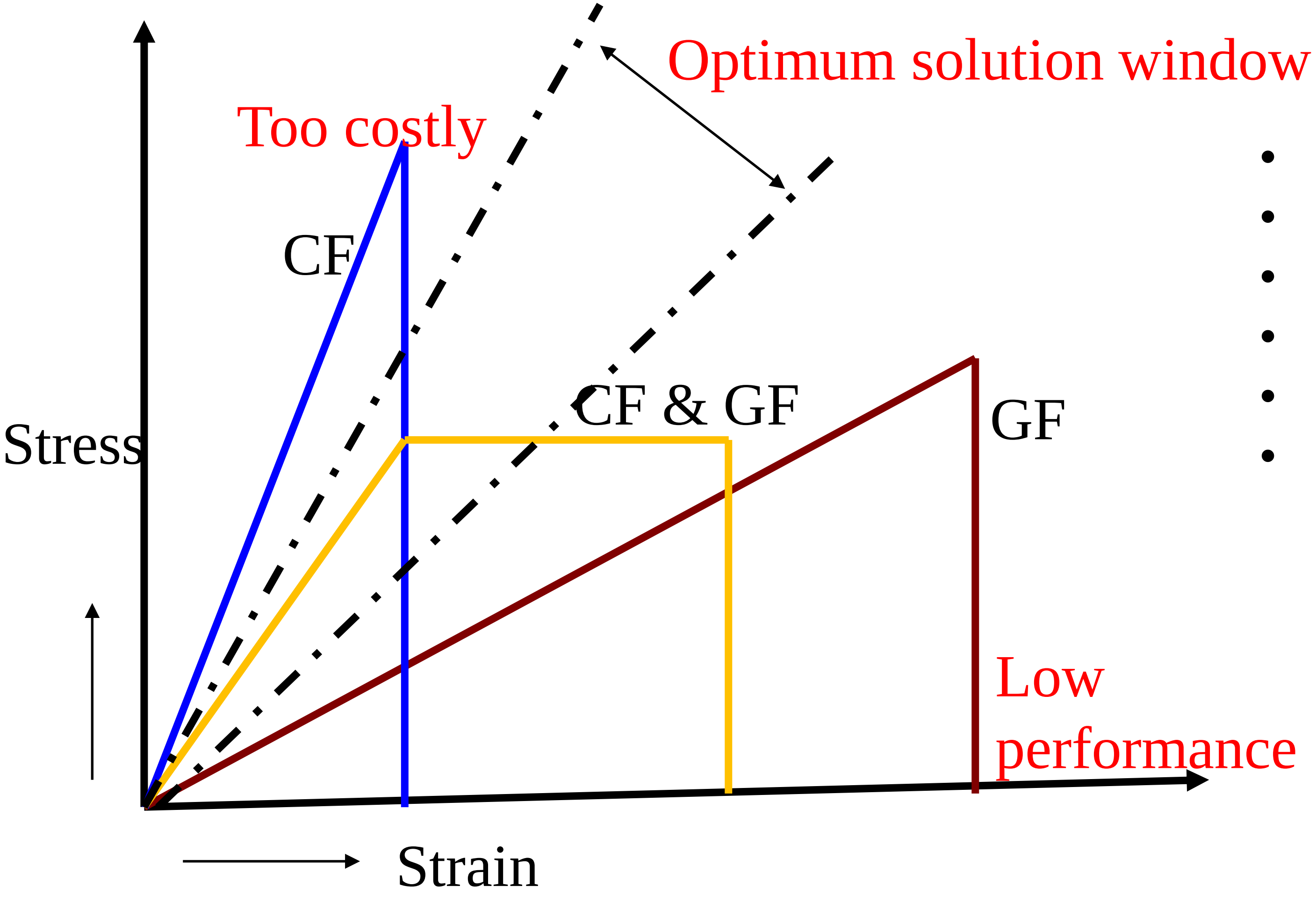
- Due to Covid-19 and contractual delays, the project could only be started beginning April 1, 2021.
- Functional requirements for the baseline battery enclosure were determined.
- A full factorial test matrix was developed for optimizing the proposed hybrid fiber material systems and develop the structural performance model. Composite preforms are being manufactured with the above permutation and combination.
- Characterization plan for the conductive wiring material was completed for the self-health monitoring technology.
- An experimental setup was designed for the development and validation of the AI/ML process monitoring technology.

Thank You!

Technical Back-Up Slides

Hybrid Fiber Composites

Tension



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

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)

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

Di Benedetto function → T_g

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