The Digital Evolution Cycle: Rethinking Auto Product Development with Continuous Fiber Thermoplastic Composites

Project ID: mat118

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Relevance: Project Objectives

1. **Achieve a 42.5% weight reduction, per FOA, or 50%, per USDRIVE Partnership Plan**
    - Base weight = **31.8 kg**
    - Target Weight = **18.28 kg**

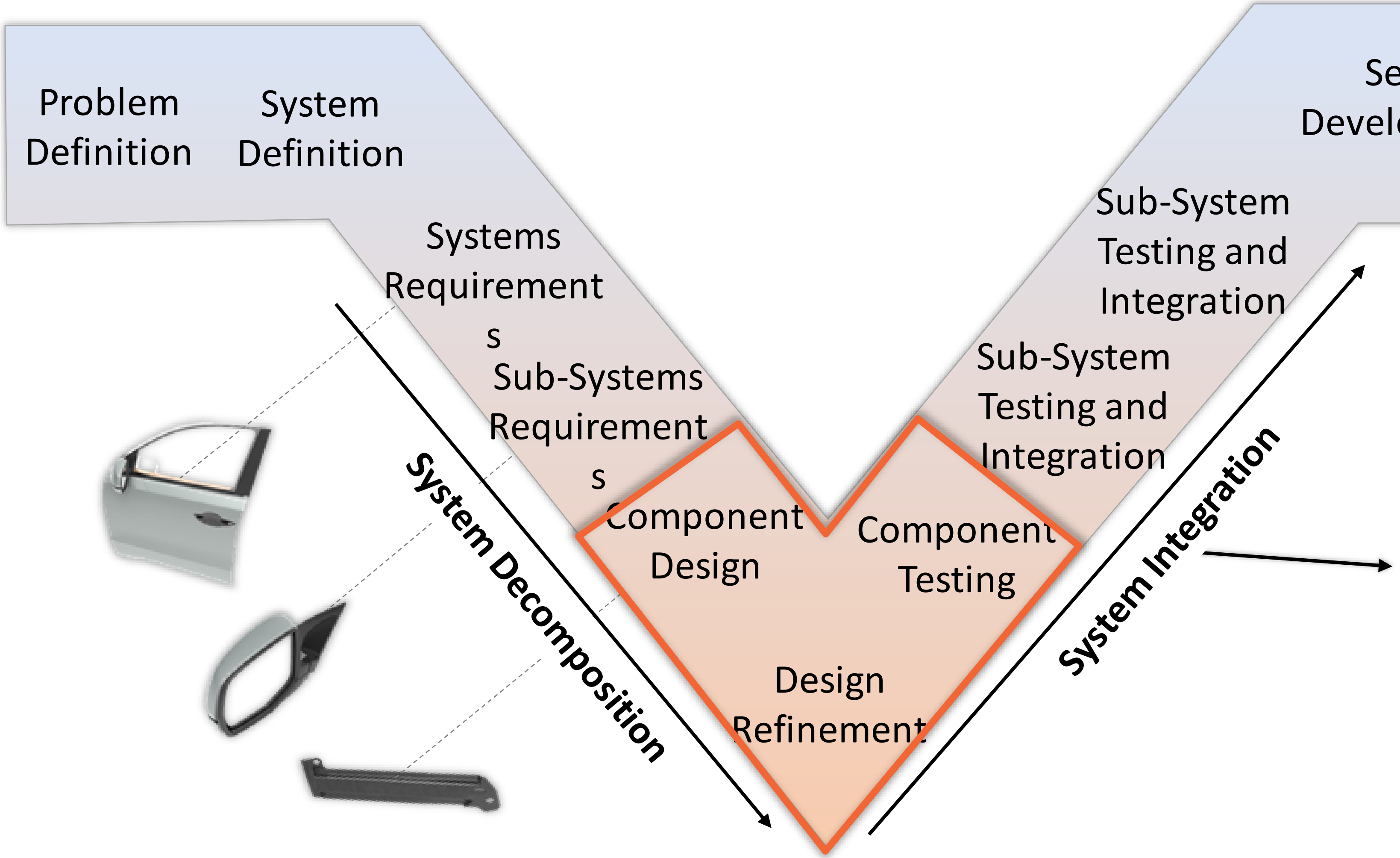
2. **Zero compromise on performance targets**
    - Similar crash performance
    - Similar durability and everyday use/misuse performance
    - Similar NVH performance

3. **Maximum cost induced is 5$ per pound saved**
    - Allowable increase = **$ 150.1 per door**

4. **Scalability**
    - Annual production of **20,000 vehicles**

5. **Recyclability**
    - European standards require at least **95 %** recyclability
    - Project goal is 100% recyclable (self-imposed)

Introduction: Automotive Product Development



Problem Definition

System Definition

Systems Requirements

Sub-Systems Requirements

Component Design

Design Refinement

Component Testing

Sub-System Testing and Integration

Sub-System Testing and Integration

Series Development

System Decomposition

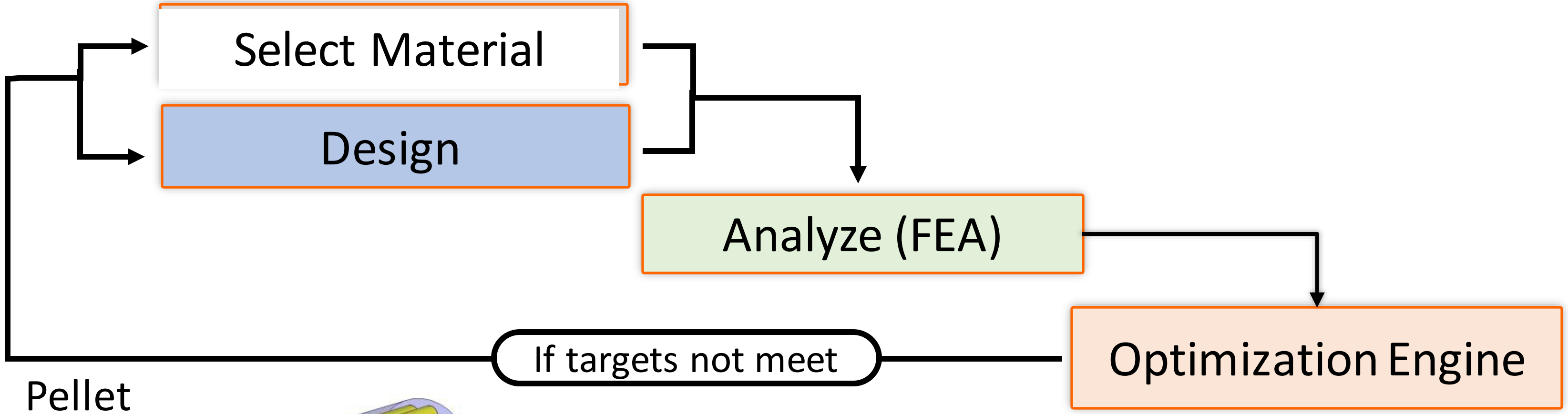
System Integration

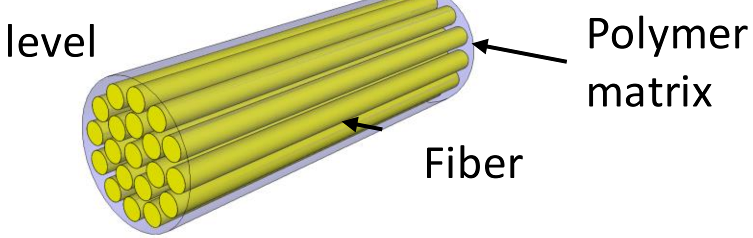
Acceptance/adoption of new materials is the conventional automotive product lifecycle that is rooted:

- Cost minimization
- Risk mitigation
- Catastrophic failure
- The lack of expertise

Systems level approach has been the mainstay in the automotive industry !

Traditional Product Development





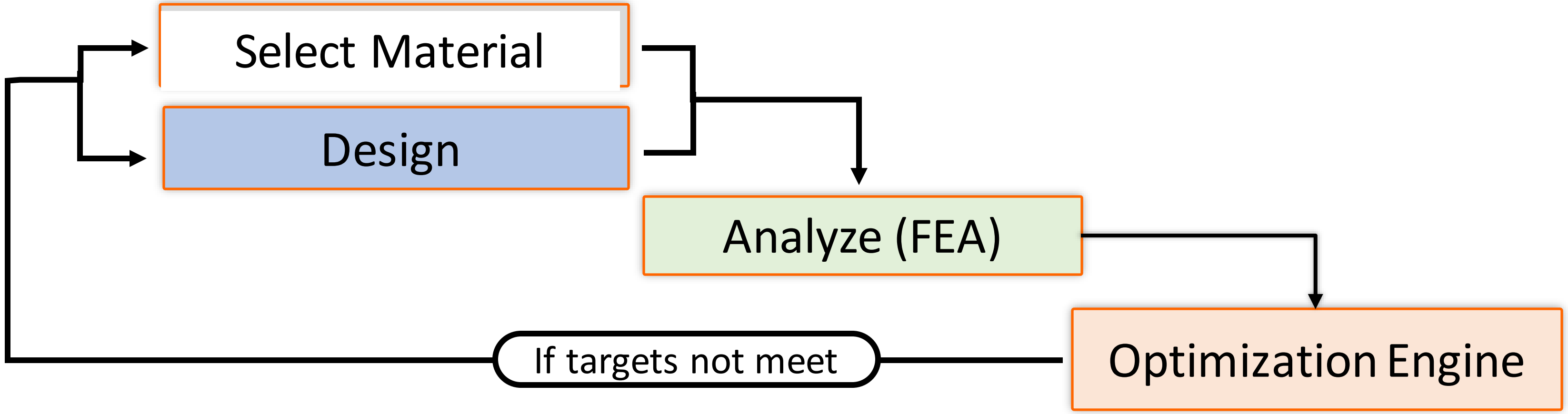
$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_{12}\end{Bmatrix} = \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

Hard to predict without secondary simulations

Salient Features

- New material deployment is often limited due to experimental constraints which is expensive.
- Inability to model/predict these manufacturing defects lead to **over engineering or underpredicting.**

Traditional Product Development



Select Material

Design

Analyze (FEA)

Optimization Engine

If targets not meet

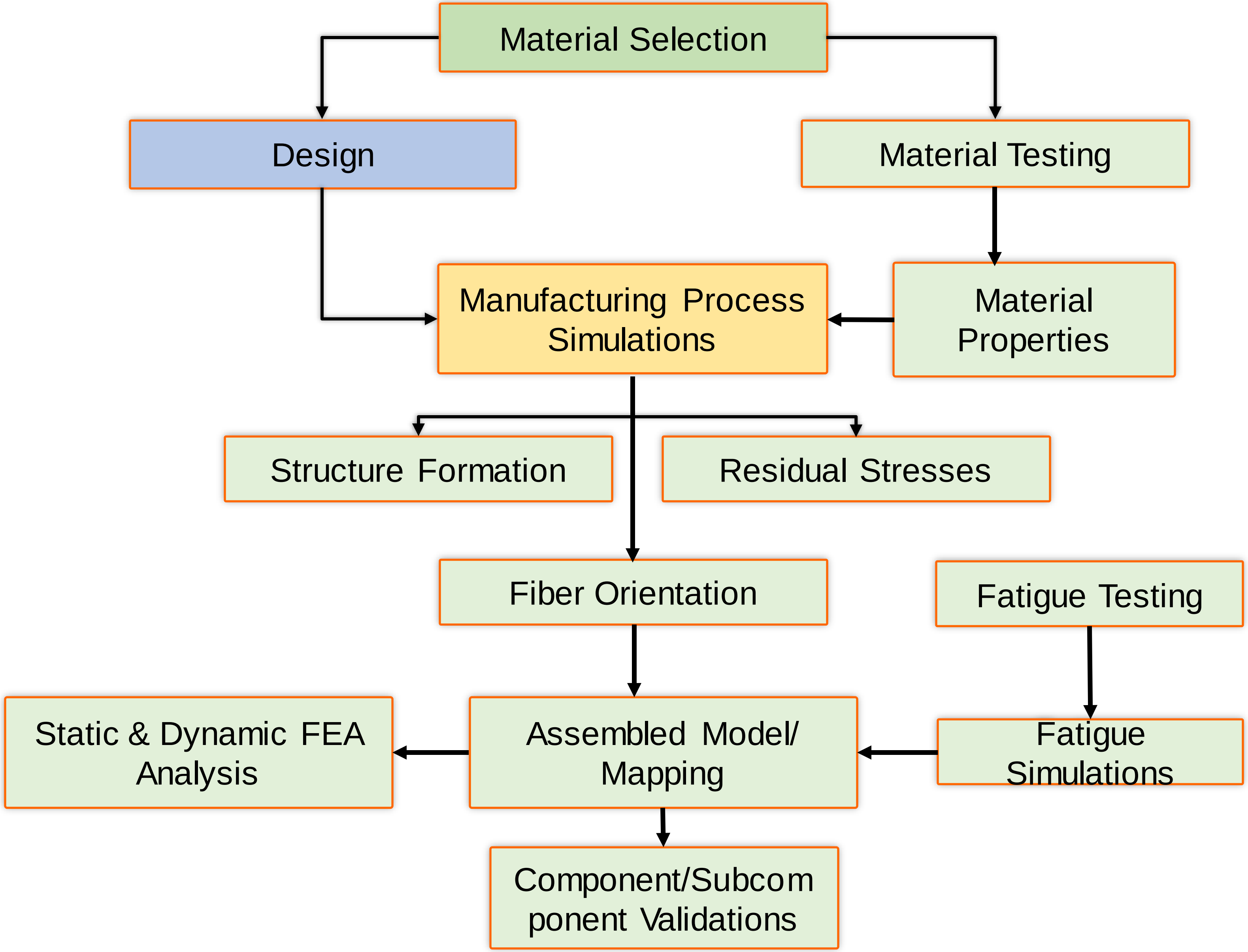
BMW i3 and i8
Revolutionary use of composites
Commercially unsuccessful

Tragic Crash in composites intensive Virgin Galactic SpaceShip 2

Salient Features

- New material deployment is often limited due to experimental constraints which is expensive.
- While coupon level tests are conducted “scaled manufacturing” effects are ignored.
- Inability to model/predict these manufacturing defects are major risks for OEMs !!!

What is Digital Lifecycle ?


Material Selection

Design

Material Testing

Manufacturing Process Simulations

Material Properties

Structure Formation

Residual Stresses

Fiber Orientation

Fatigue Testing

Static & Dynamic FEA Analysis

Assembled Model/ Mapping

Fatigue Simulations

Component/Subcomponent Validations

Salient Features

- Computational material science broadens material options.
- Coupons are manufactured and characterized in order to obtain manufacturing and mechanical inputs !
- Multiple simulation and validation steps provide OEMs the confidence to adopt new materials

Design Approach

Phase 1

Benchmarking & Target Definition


Frame 60% Reduction


Window 20% Reduction


Electronic 0% Reduction


Trim 30% Reduction
Or elimination

Baseline Door (This project) 31.1 kg

Material Data Generation

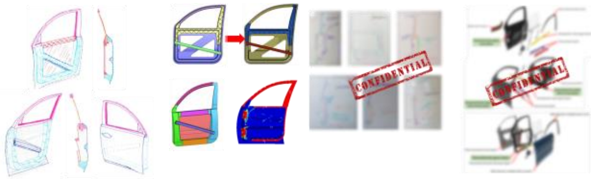
$$\begin{Bmatrix} f_1 \\ V_1 \\ M_1 \\ f_2 \\ V_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 & 0 & -\frac{AE}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{AE}{L} & 0 & 0 & \frac{AE}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}$$

Mat 8 (Static Simulations)
MAT 54 (Dynamic Simulations)

Unidirectional PA 6 CF 50 wt %
Woven PA 6 CF 50 wt %

Phase 2

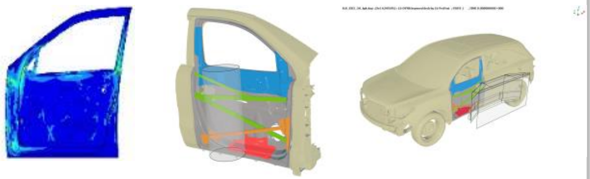
Concept Development



Extensive concept development
Systems level approach
Aggressive parts consolidation

Concepts developed	6 → 3 → 1
Baseline Structural Parts	17
ULCW Door Structural Parts	8

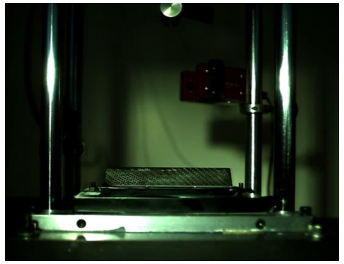
FEA Simulations



Door optimized for and passes
8 Static Cases
(Door sag, Sash rigidity …)
3 Dynamic cases
OEM requirement > FMVSS 214 targets

Phase 3

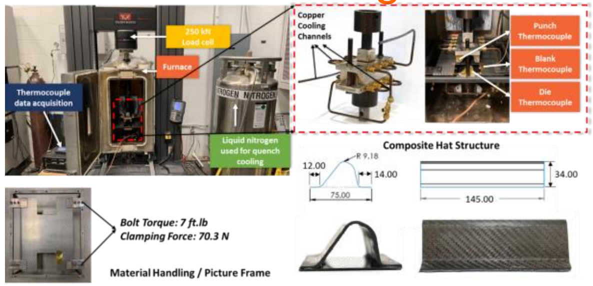
Subcomponent Testing



Calibrating and Validating MAT 54 Cards in Dynamic environment

Cost Analysis	Parametric cost model
Fit and Finish	Low cost prototype fabricated (Passed)

Thermoforming Trials



Developing a manufacturing to response pathway + Vendor selection (Lanxess)

Phase 4

Tooling + Prototyping

Leveraging experience of suppliers like Proper Tooling + Lanxess

Glass & Carbon Doors Manufactured & Assembled
Quasi static & Dynamic tests performed

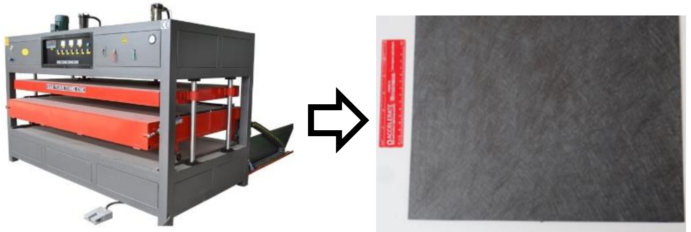
Testing

SOP's for static and dynamic tests to be finalized by OEM

Material Data Generation

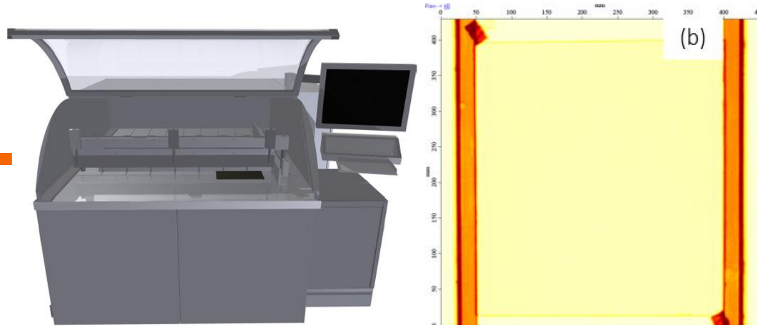
Coupon Manufacturing

Barrday
ADVANCED MATERIAL SOLUTIONS
LANXESS
Energizing Chemistry



Material Processing

- Plaques were manufactured in line with the final processing route selected



Sample Screening and Preparation

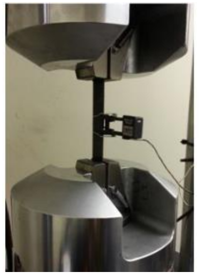
- Plaques were scanned for voids using a CT scanner.
- 0 and 90 Samples were cut using a diamond coated blade.Tabbed using epoxy-based adhesives.

Bonding Strain Gauges

- Bi-axial strain gauges were used in order to record true strain.

Material testing

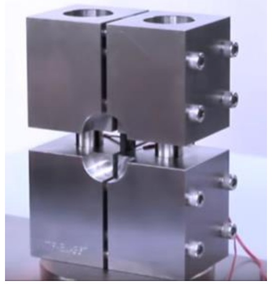
Tension



ASTM D 039

- Samples tested in 0° and 90° orientations
- At least 5 samples were tested
- Crosshead speed of 2.5 mm/min

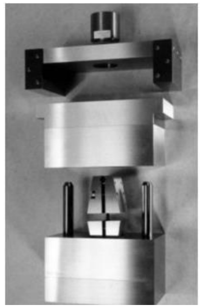
Compression



ASTM D6641

- Samples tested in 0° and 90° orientations
- At least 5 samples were tested
- Crosshead speed of 1.3 mm/min

Shear

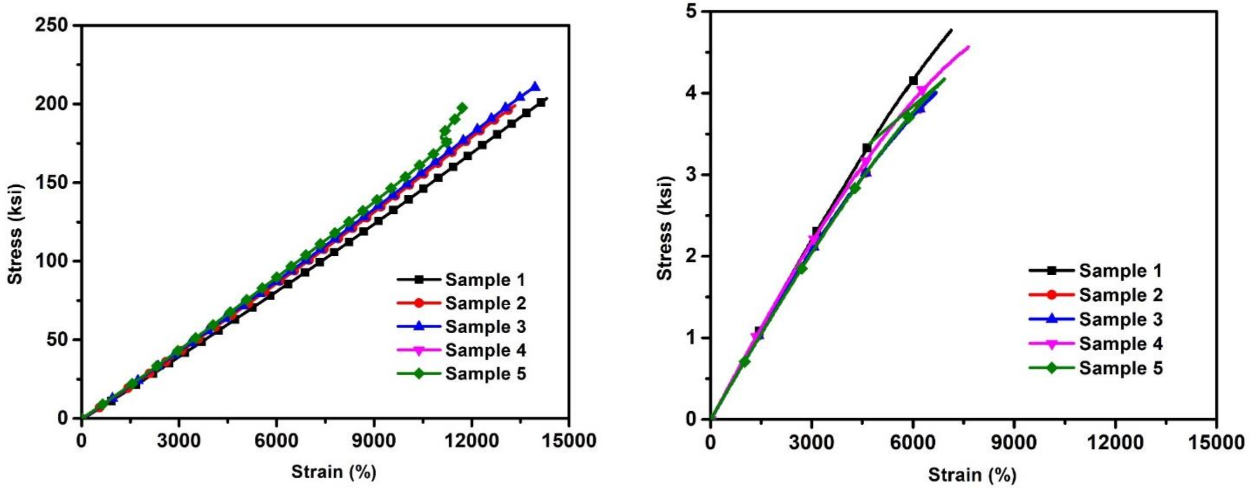


ASTM D3410

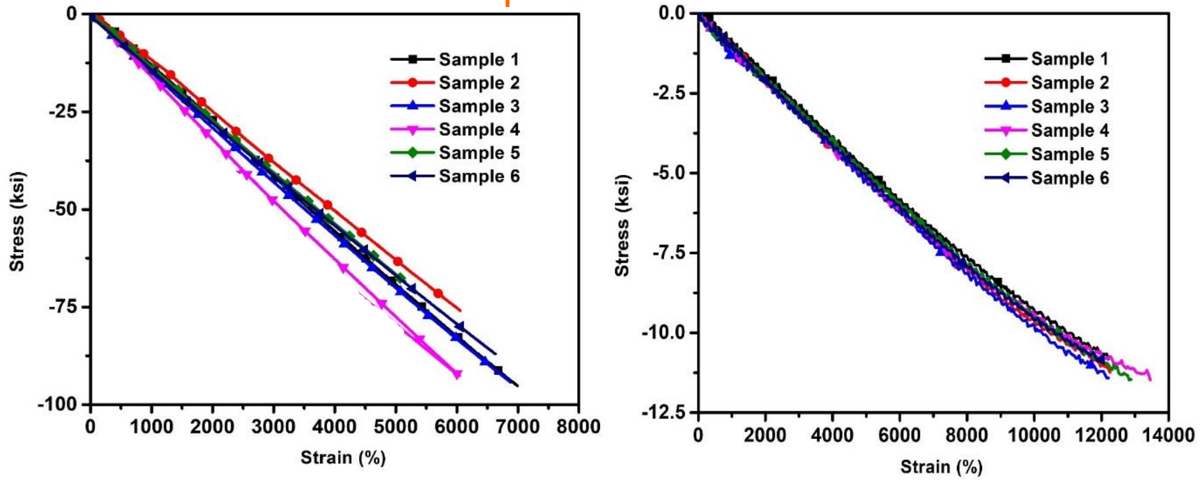
- Samples tested in 45° orientations
- At least 5 samples were tested
- Crosshead speed of 1.5 mm/min

Endless Fiber Reinforced Polymer

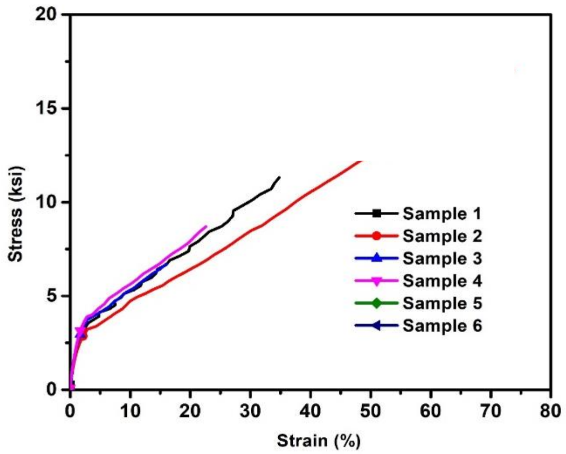
Tension 0 and 90



Compression 0 and 90



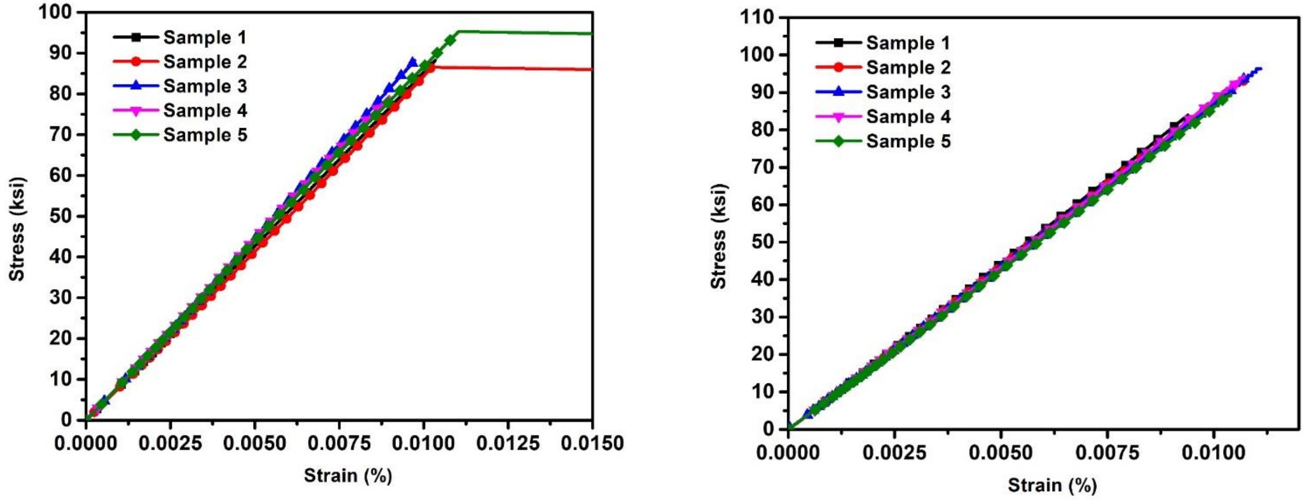
In-Plane Shear (Compression)



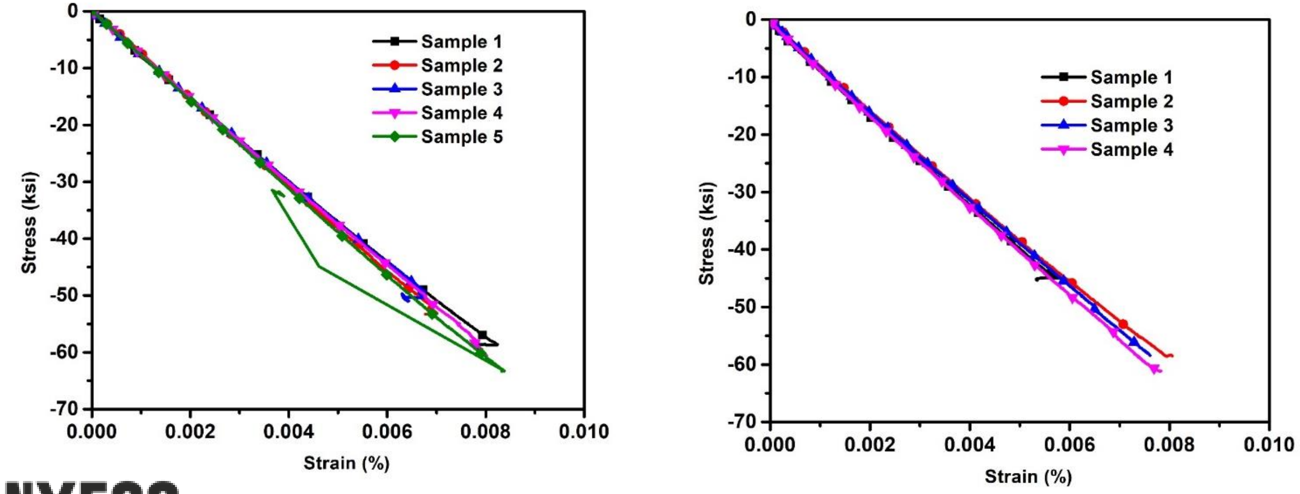
- In-plane shear behavior was characterized using the compression tests on a [±45º] laminate.
- Tension mode allowed fiber rotation due to the thermoplastic matrix toughness and axial strain was measured using optical methods with markers and high-resolution video cameras.
- Compression mode was performed using the shear-loaded compression method (IITRI) and strains measured to the limit of strain gages.

Woven Fiber Reinforced Polymer

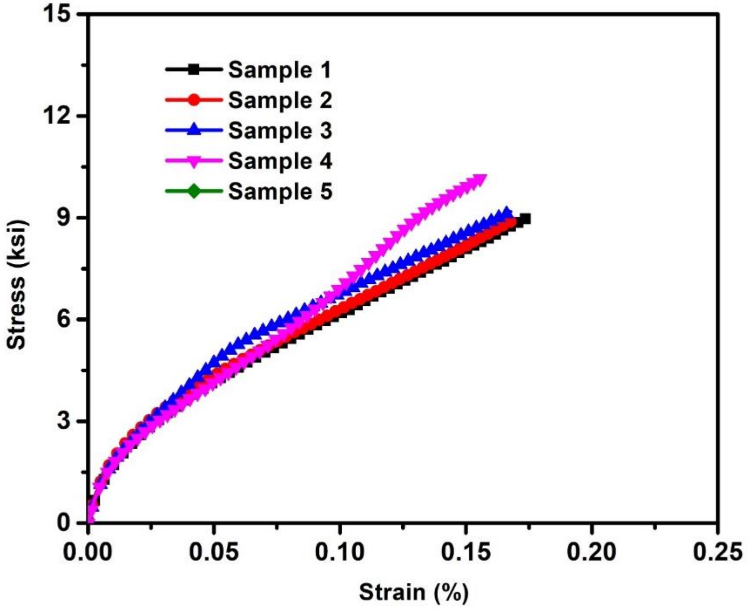
Tension 0 and 90



Compression 0 and 90



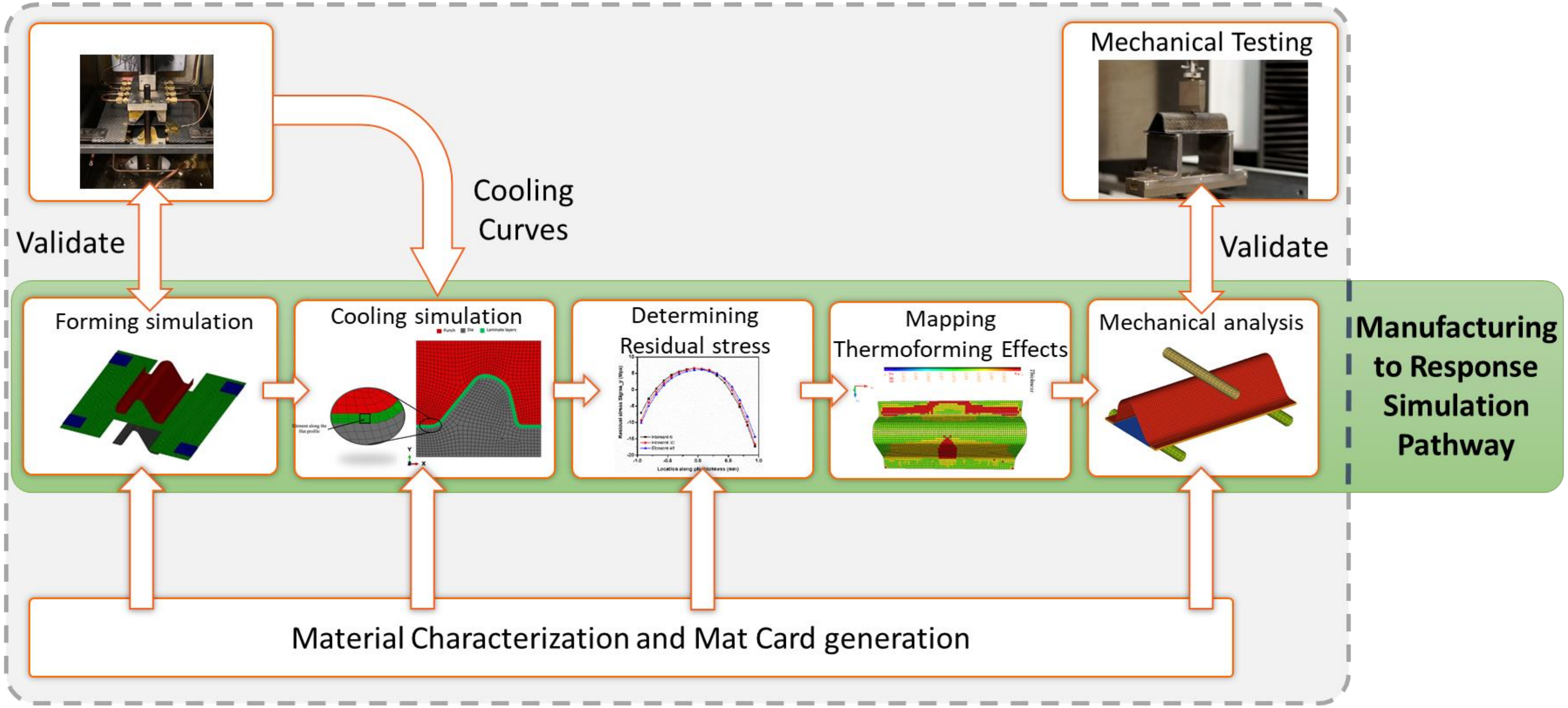
In-Plane Shear (Compression)



- Compression mode was performed using the shear-loaded compression method (IITRI) and strains measured to the limit of strain gages.
- Load-displacement response was used to identify plateau stress and displacement limits.

Modeling Pathway

Manufacturing-to-Response Pathway



Mechanical Testing

Cooling Curves

Validate

Validate

Forming simulation

Cooling simulation

Determining Residual stress

Mapping Thermoforming Effects

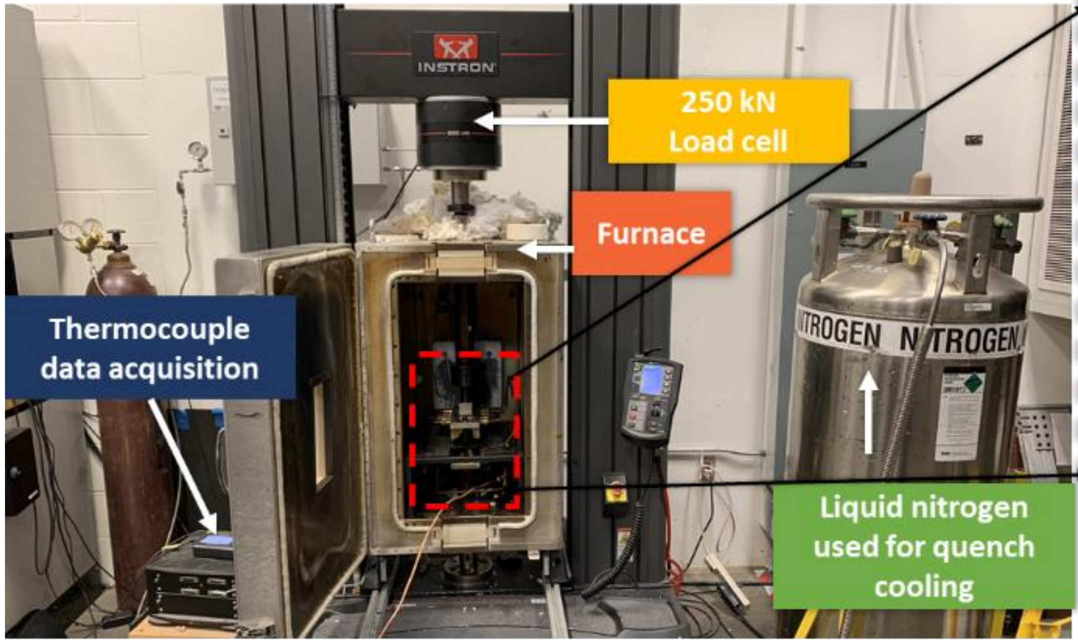
Mechanical analysis

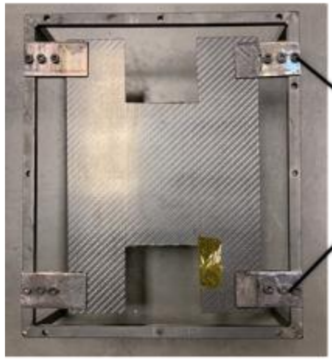
Manufacturing to Response Simulation Pathway

Material Characterization and Mat Card generation

- Compared to other approaches the present work establishes a complete pathway for end-to-end analysis of thermoformed continuous carbon fiber reinforced Polyamide 6 (PA6) composite structure.
- To the best of the authors knowledge this is the **first synergistic experimental and numerical approach** that ***wholly captures process induced effects and its impact on static mechanical performance.***

Thermoforming Setup

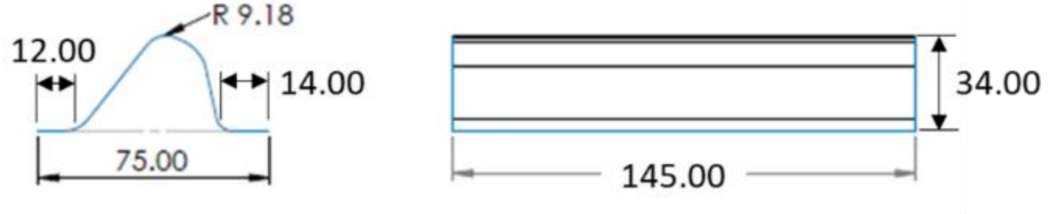




Bolt Torque: 7 ft.lb
Clamping Force: 70.3 N

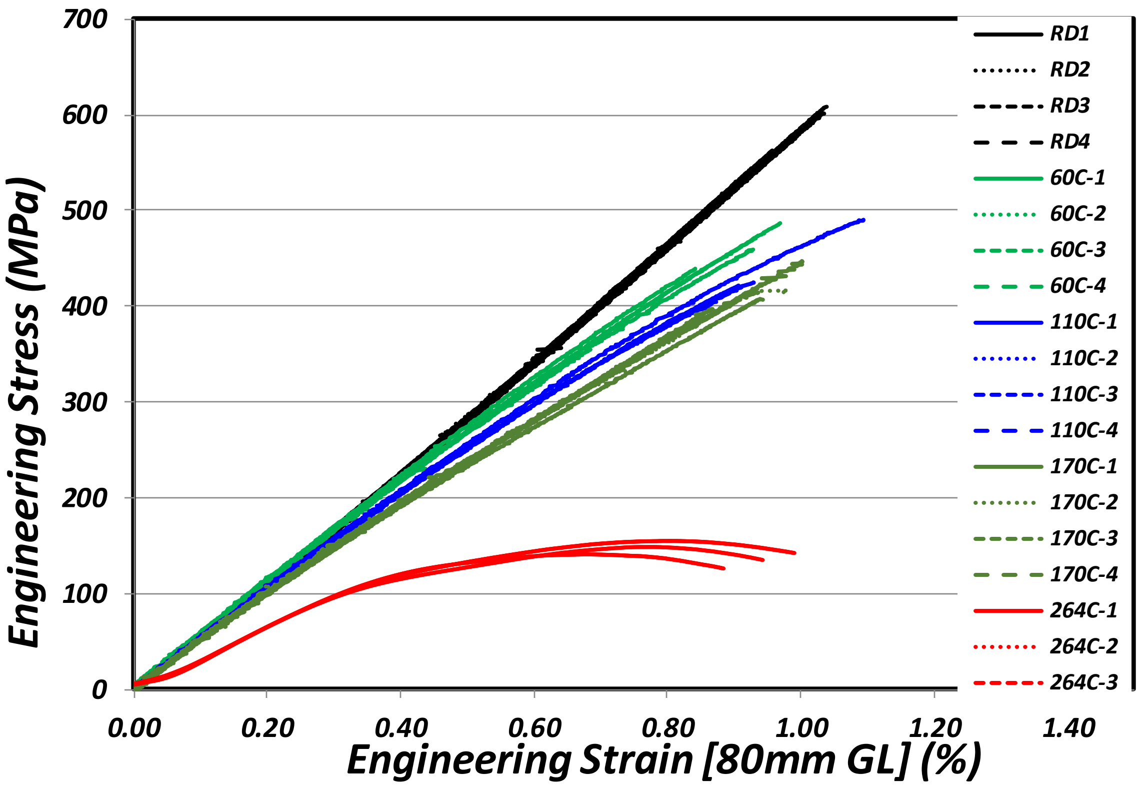
Material Handling / Picture Frame

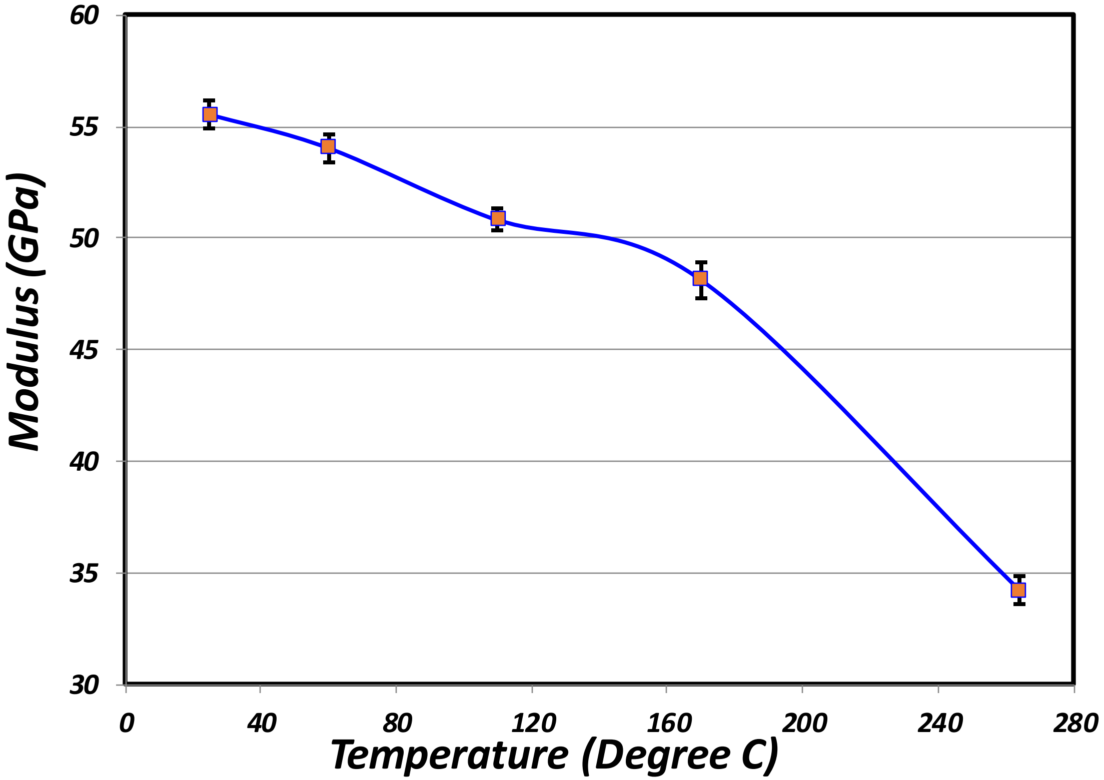
Composite Hat Structure



First tool to incorporate copper cooling channels for liquid nitrogen in order to quench cool a geometrically complex formed component !

Experimental Inputs to Digital Lifecycle

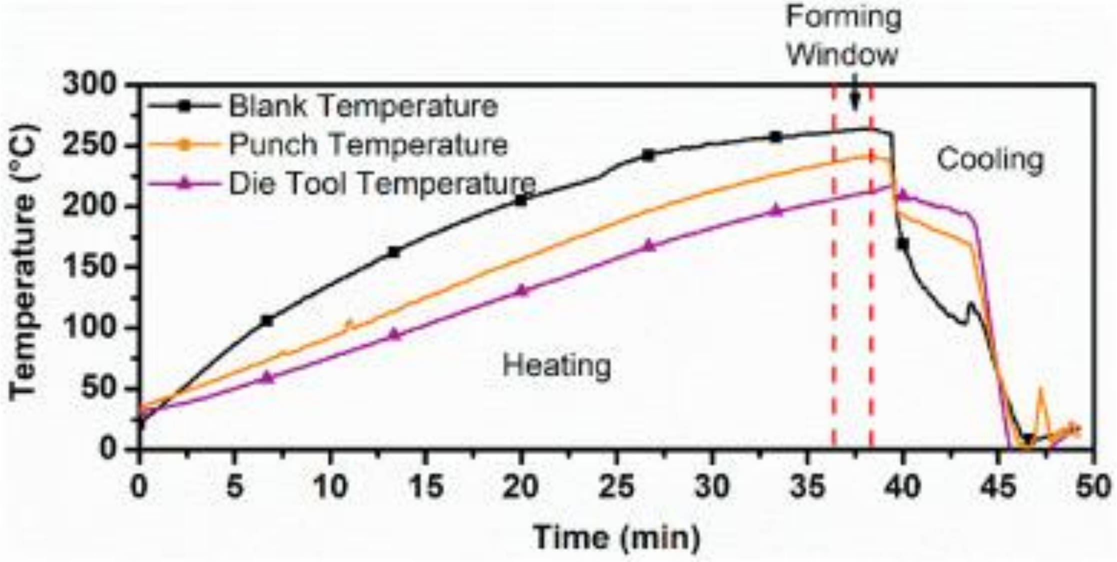


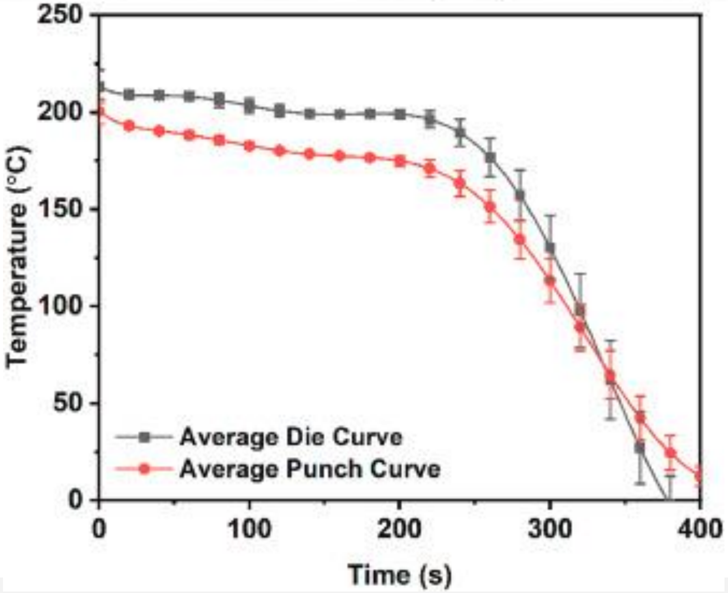


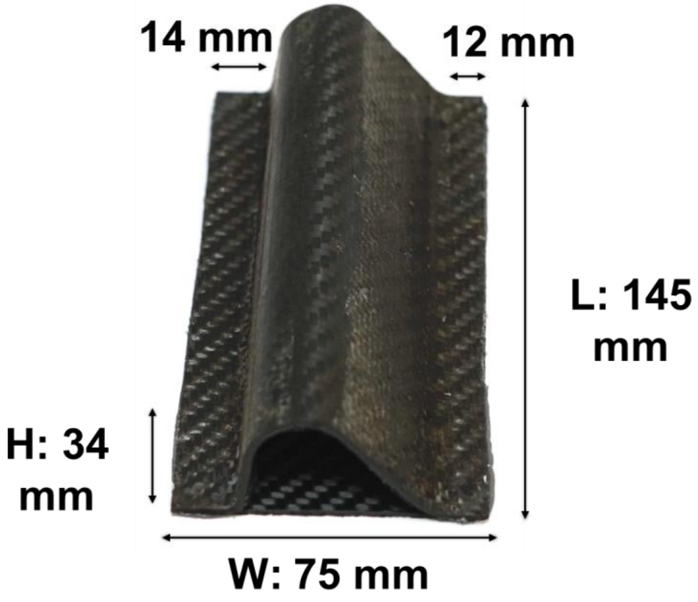
Property		**Carbon/PA6**
Specific Heat [$J/kg\ K$] **ASTM E 1269**	**@ 25°C**	1206.65 ± 24.57
	@ 45°C	1304.96 ± 21.36
	@ 60°C	1364.76 ± 18.64
Thermal conductivity [$W/m\ K$]		0.682 ± 0.001

- Coupon level mechanical and thermal tests were carried out for generating mechanical material card and inputs for MTR pathway.

Experimental Subcomponent Runs







- Thermocouples on the tool and material provided important inputs for digital lifecycle.
- Good consolidation was achieved in all 3 hat sections and adhesive appliation

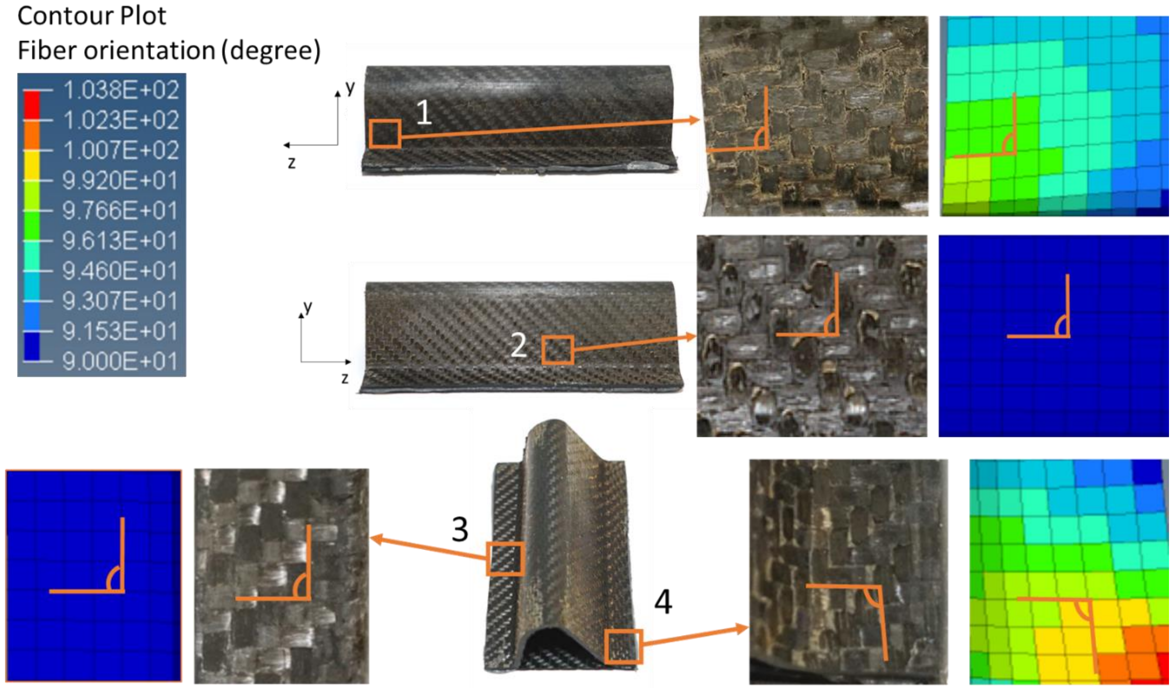
Thermoforming results: Thickness Variation

Experimental Mean Thickness ± Std Dev

Simulated Thickness

- Good consolidation was achieved in all 3 hat sections
- Maximum thickness:2.01mm is observed at location 5 with the standard deviation of 0.008mm.
- Minimum thickness of 1.97mm is observed along the flatter edges locations 1 and 3 with the standard deviation of 0.01mm.
- ***A comparison between the measured thickness and predicted thickness shows a good agreement***

Thermoforming results: Fiber Orientation

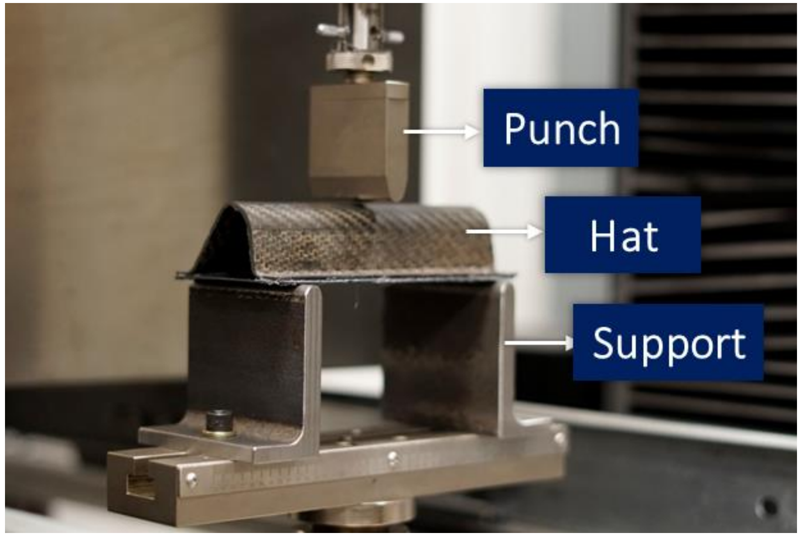


Location	Experimental Average (°)	Std.	Simulation	%Difference
1	96.76	1.42	95.77	**1.02**
2	91.90	3.19	90.18	**1.87**
3	90.93	0.81	90.00	**1.03**
4	100.08	5.17	96.72	**3.36**

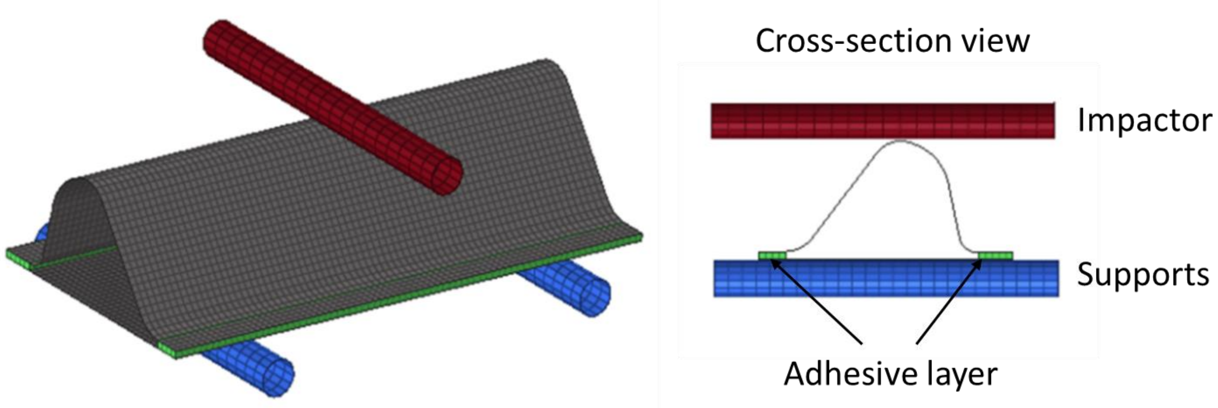
- A comparison between the experimental orientation and the simulated prediction shows good agreement
- Fibers in directions 1 and 2 initially 90° apart
- The maximum fiber angle of 103° can be observed from the contour plot near location 4, which means a fiber reorientation of 13°

Quasi Static Experiments and Modelling

Experiments	Simulation

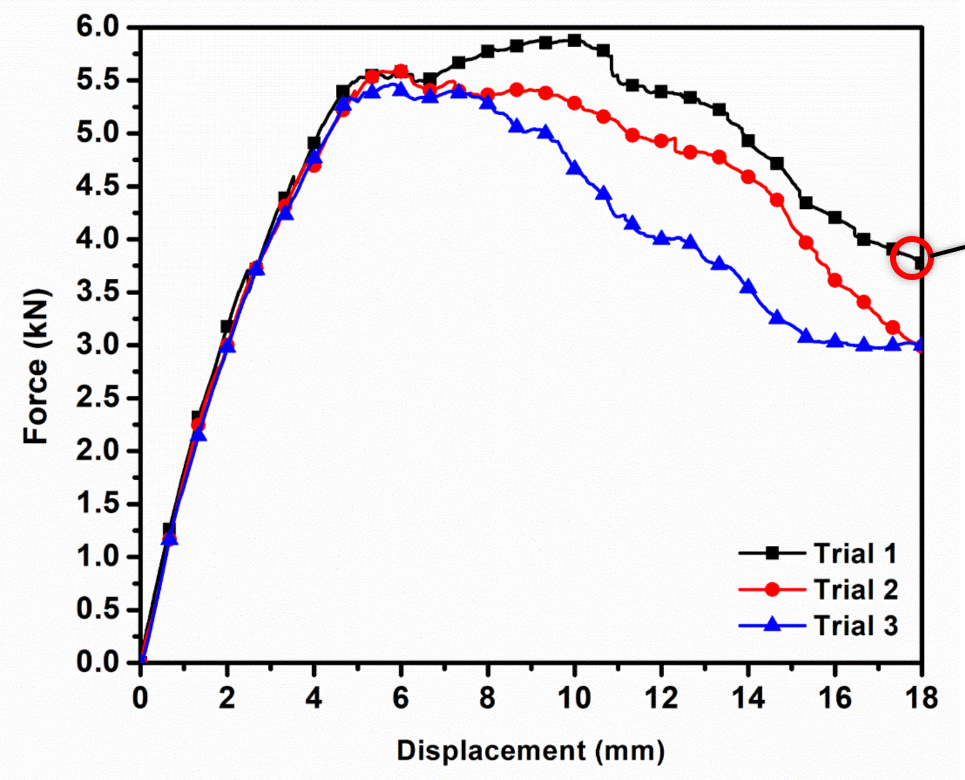


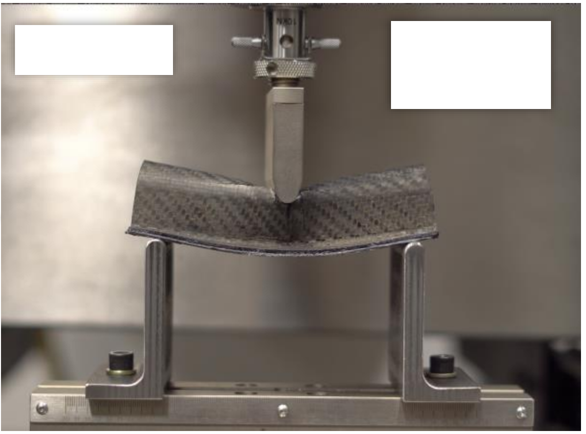
- **Crosshead Speed:** 1/mm/min
- **Support Span:** 119.3 mm
- **Punch Radius:** 10 mm
- **Support Radius:** 10 mm

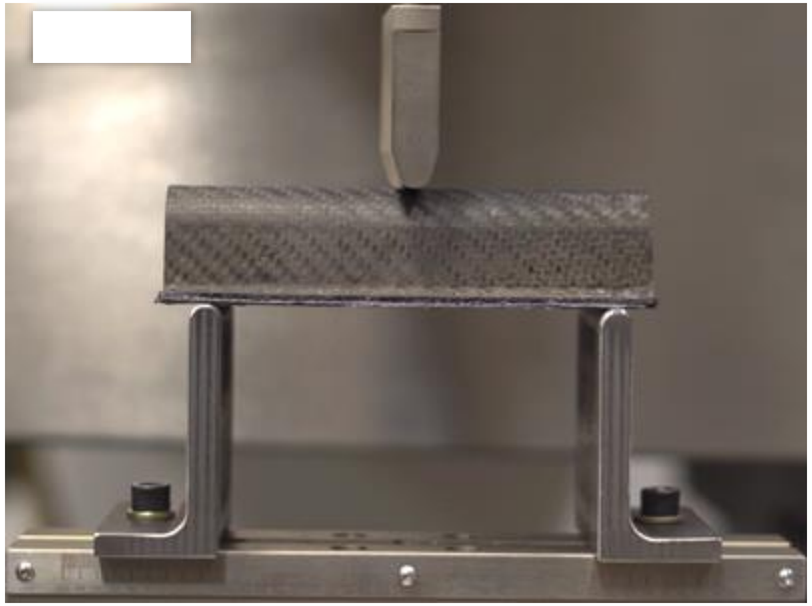


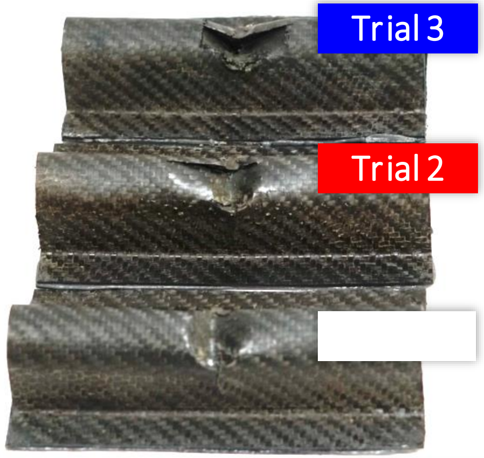
- ***Process induced effects namely fiber orientations, thickness variations and residual stresses included.***
- **Software:** LS-Dyna
- **Material model:** LS-DYNA material law MAT 58 (MAT_Laminated_Composite_fabric), anisotropic behavior of composite
- **Damage mechanics:** Matzenmiller-Lubliner-Taylor model.

Experimental: Quasi Static Performance



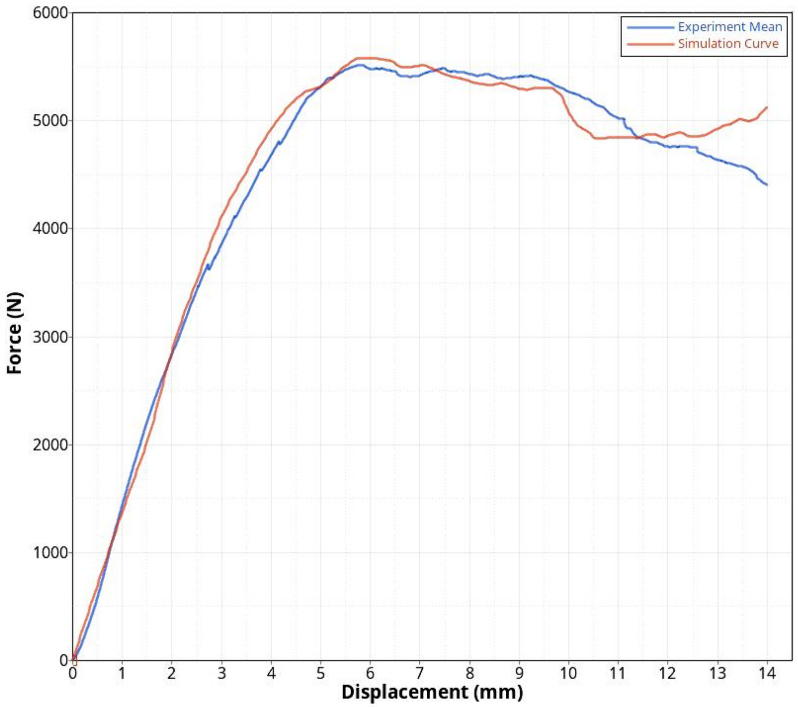


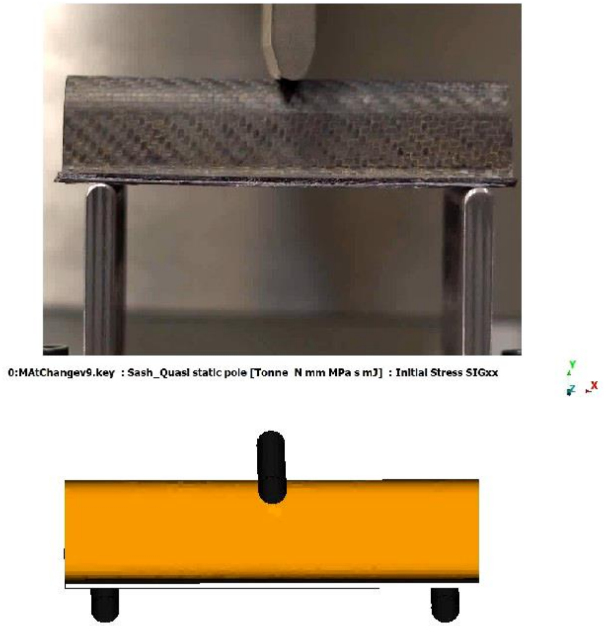


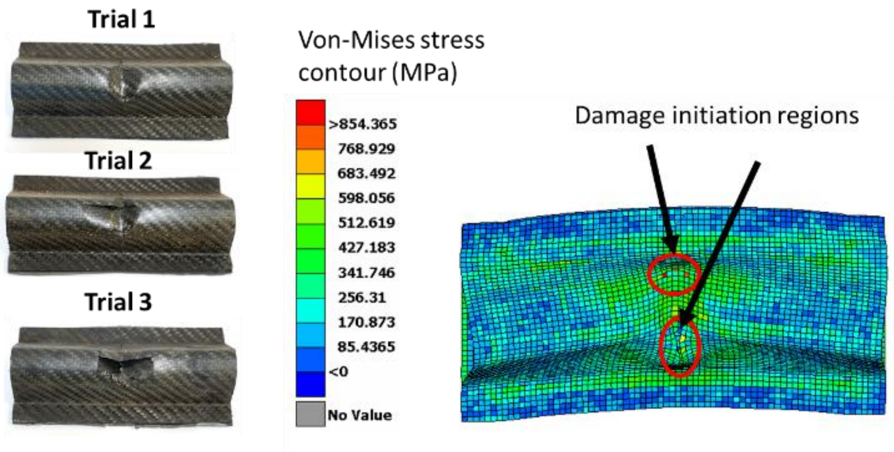


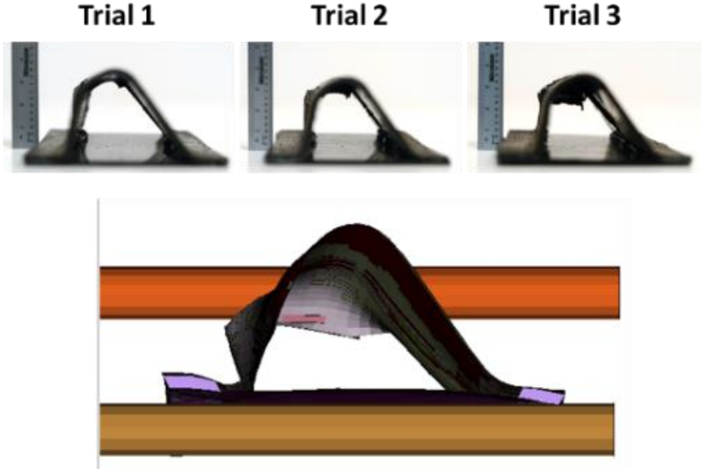
- Linear elastic region of all 3 trials is extremely repeatable.
- Initiation of failure is repeatable.
- Peak load and progressive damage vary slightly.

Model Validation: Quasi Static Performance





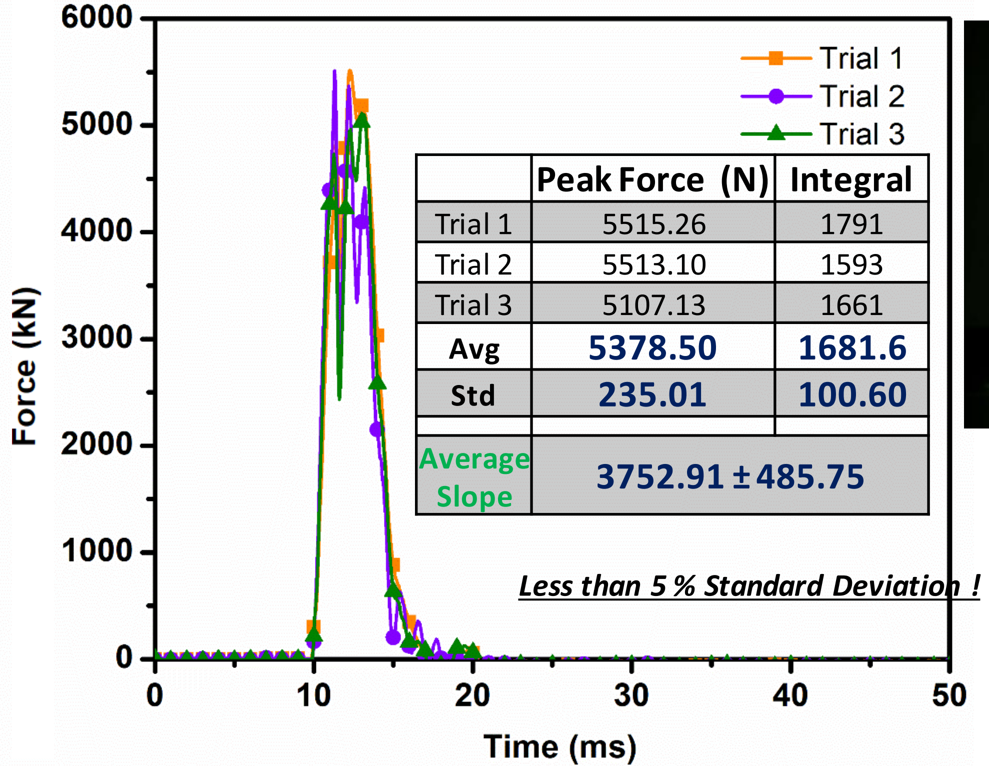




- A comparison between the experimental orientation and the simulated prediction shows good agreement.

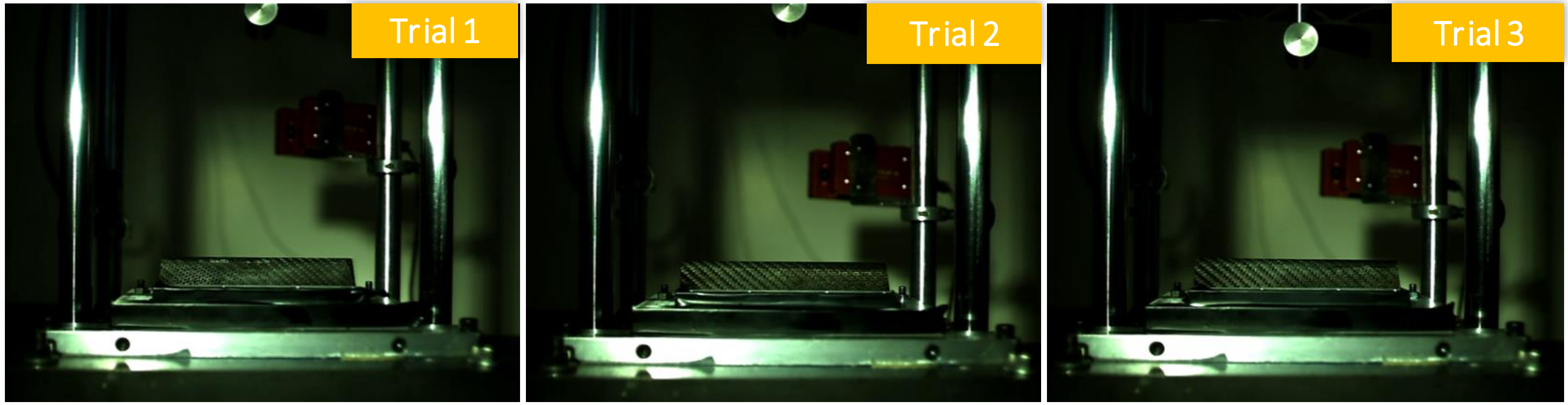
- The damage behavior is consistent with the experimental results.

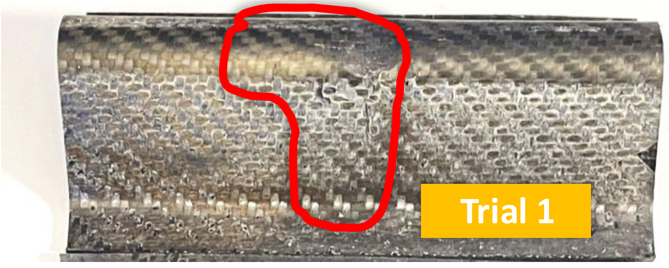
Experimental: Dynamic Performance

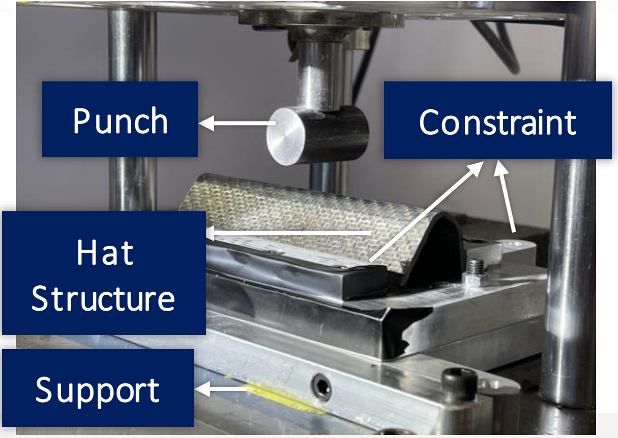


	Peak Force (N)	Integral
Trial 1	5515.26	1791
Trial 2	5513.10	1593
Trial 3	5107.13	1661
Avg	**5378.50**	**1681.6**
Std	**235.01**	**100.60**
Average Slope	**3752.91 ± 485.75**	

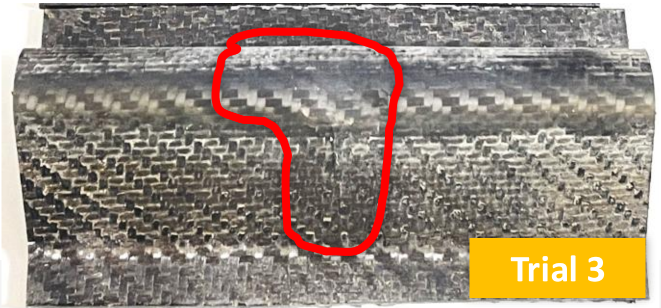
Less than 5 % Standard Deviation !



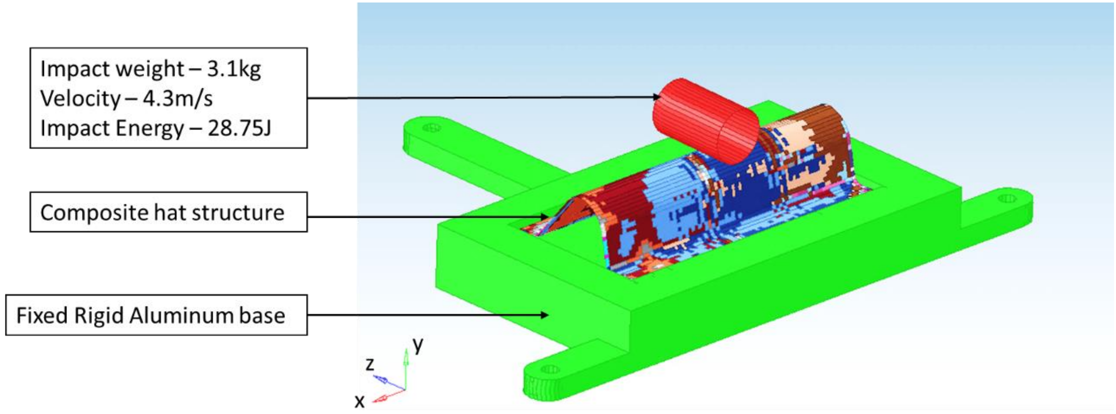




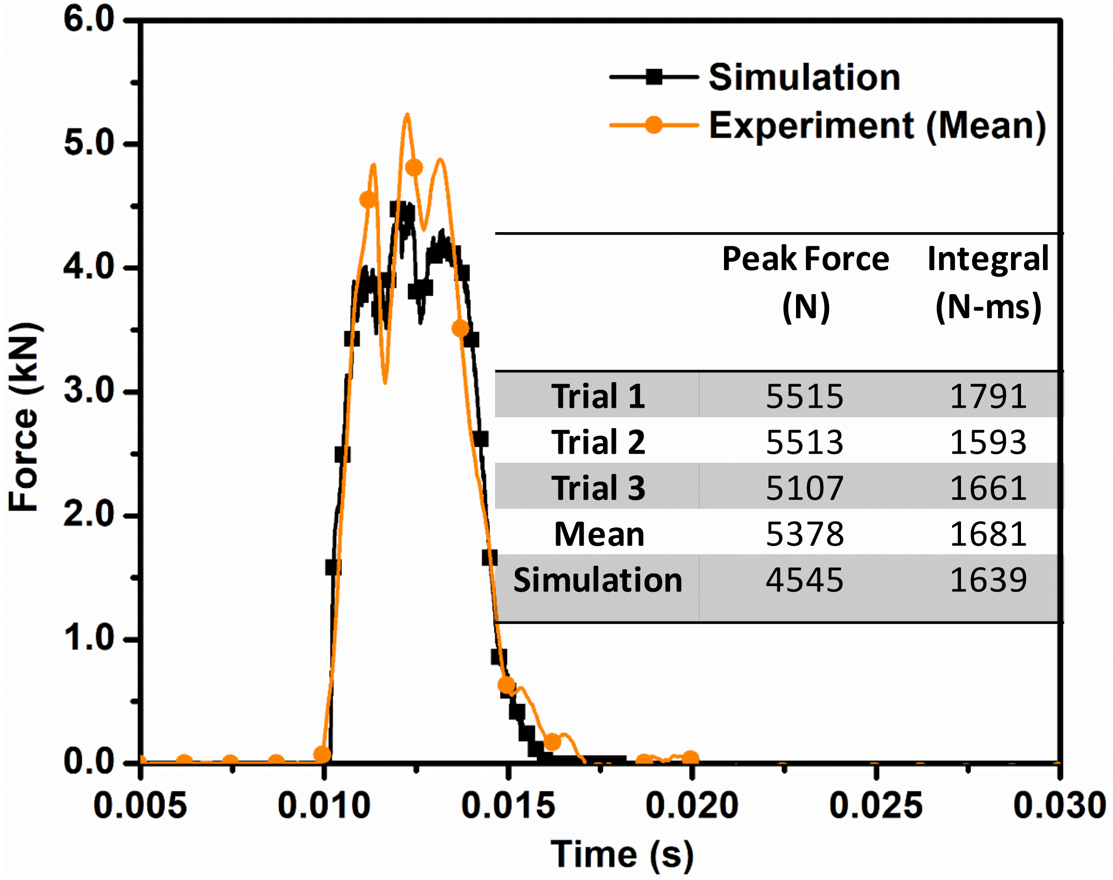
Impactor Diameter: **1 in**
Impactor Weight: **3.1 kg**
Height of Drop: **0.94 m**
Velocity at Impact: **4.3 m/s**
Energy: **28.65 J**
Peak Load: **5514.18 ± 235 N**



Model Validation: Dynamic Performance



- **Software:** LS-Dyna
- **Material model:** LS-DYNA material law MAT 54(Enhance composite damage)
- **Damage mechanics:** Chang-Chang failure model



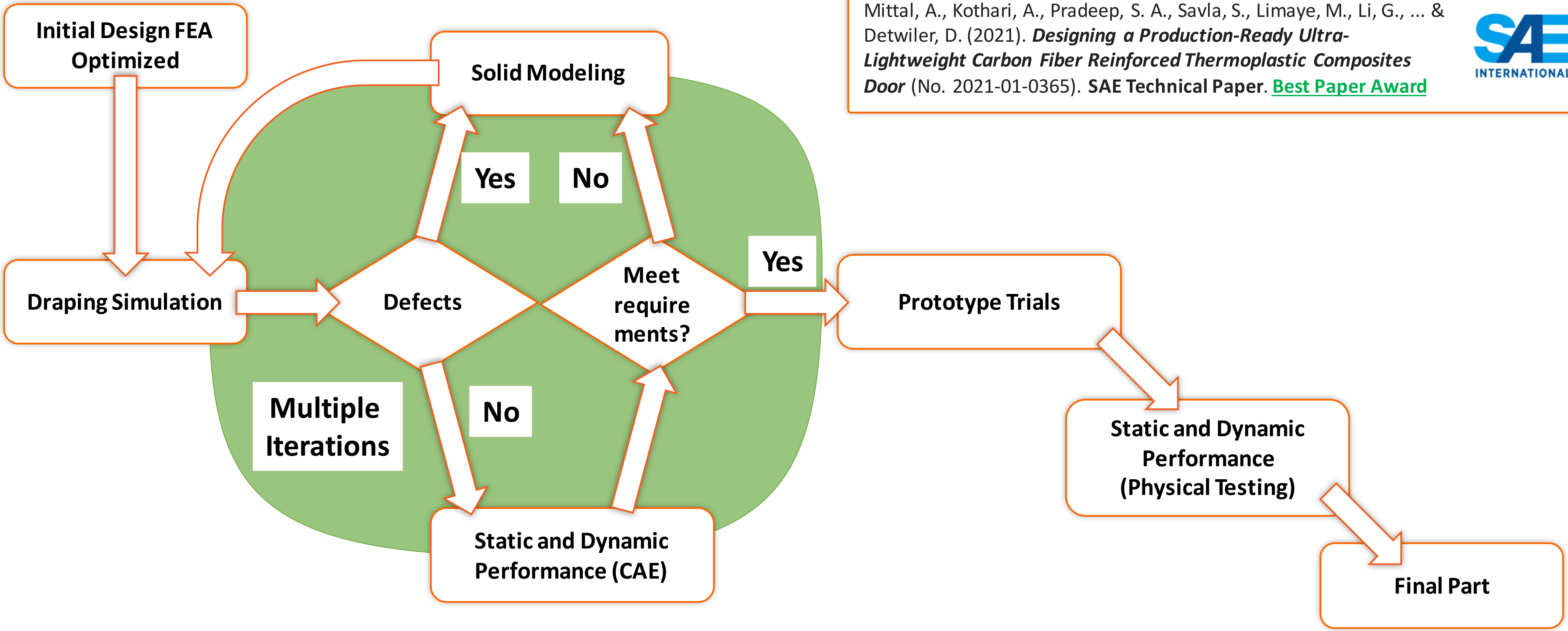
	Peak Force (N)	Integral (N-ms)
Trial 1	5515	1791
Trial 2	5513	1593
Trial 3	5107	1661
Mean	5378	1681
Simulation	4545	1639

- A comparison between the experimental results and the simulated prediction shows good agreement.
- The damage behavior is consistent with the experimental results.

Thermoforming process effects on structural performance of carbon fiber reinforced thermoplastic composite parts through a manufacturing to response pathway

Journal of Composites Part B
Impact factor: 13.1

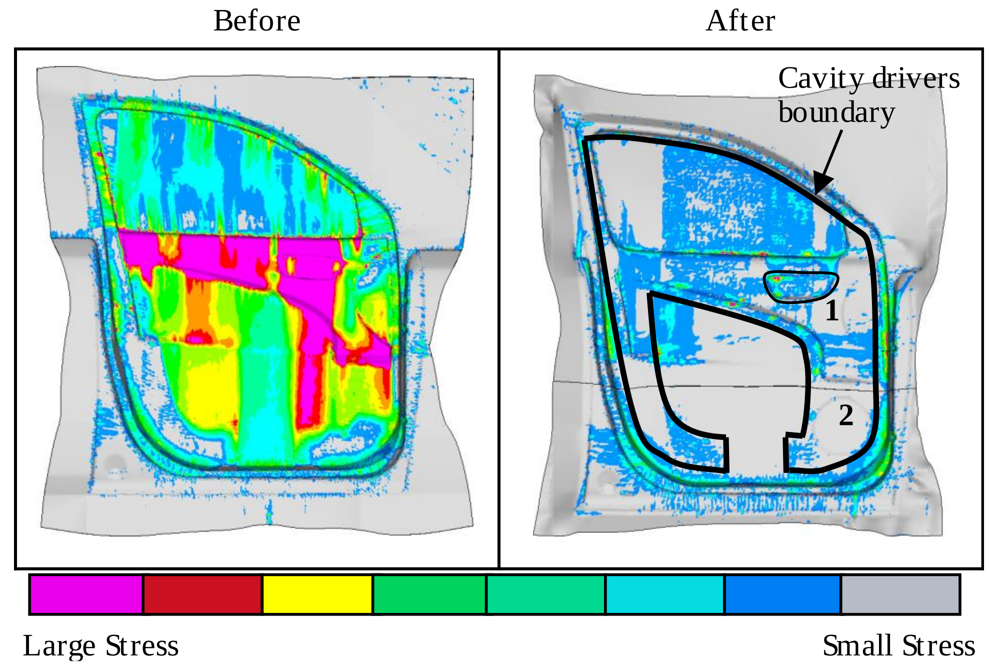
Manufacturing Simulations: Inner Panel

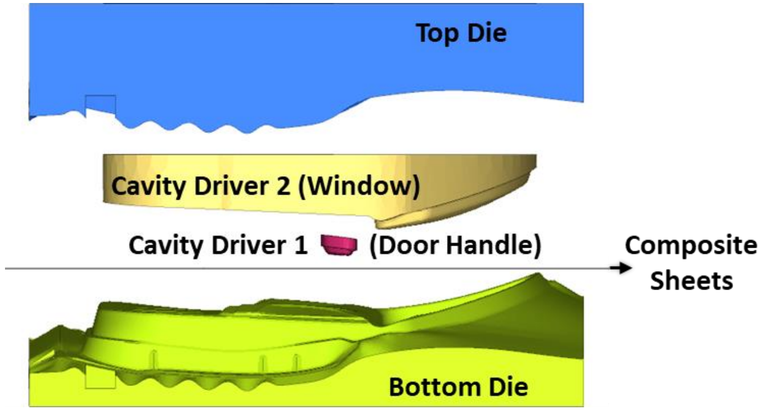


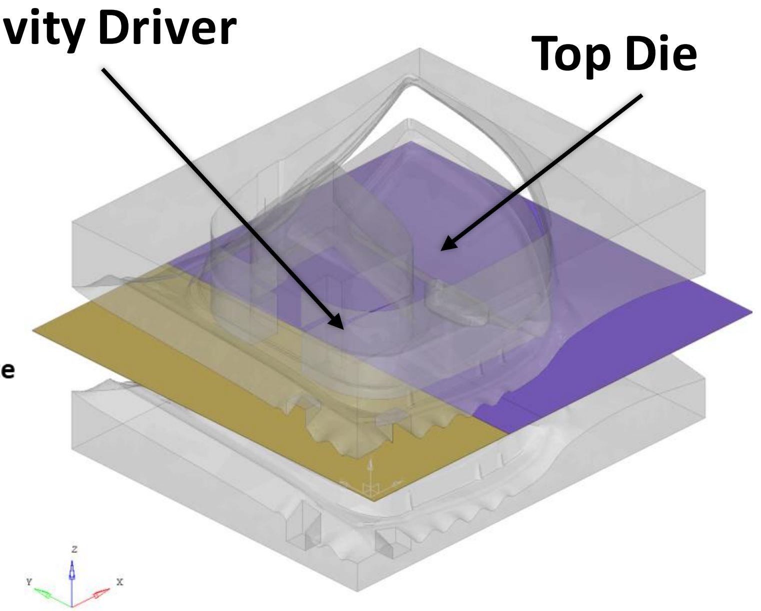
Mittal, A., Kothari, A., Pradeep, S. A., Savla, S., Limaye, M., Li, G., ... & Detwiler, D. (2021). ***Designing a Production-Ready Ultra-Lightweight Carbon Fiber Reinforced Thermoplastic Composites Door*** (No. 2021-01-0365). **SAE Technical Paper.** Best Paper Award

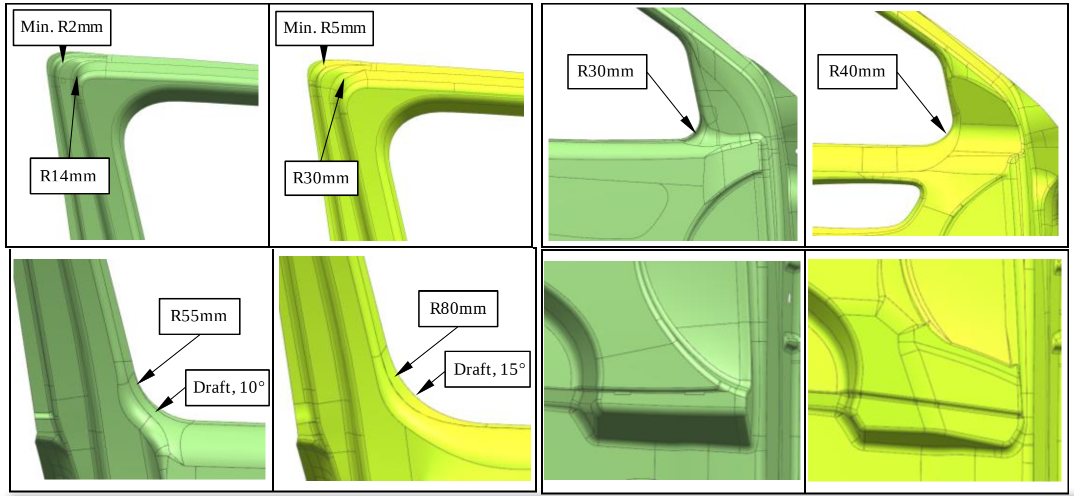
Design optimization for reduction of manufacturing defects using draping simulations with support from Lanxess

Drapability









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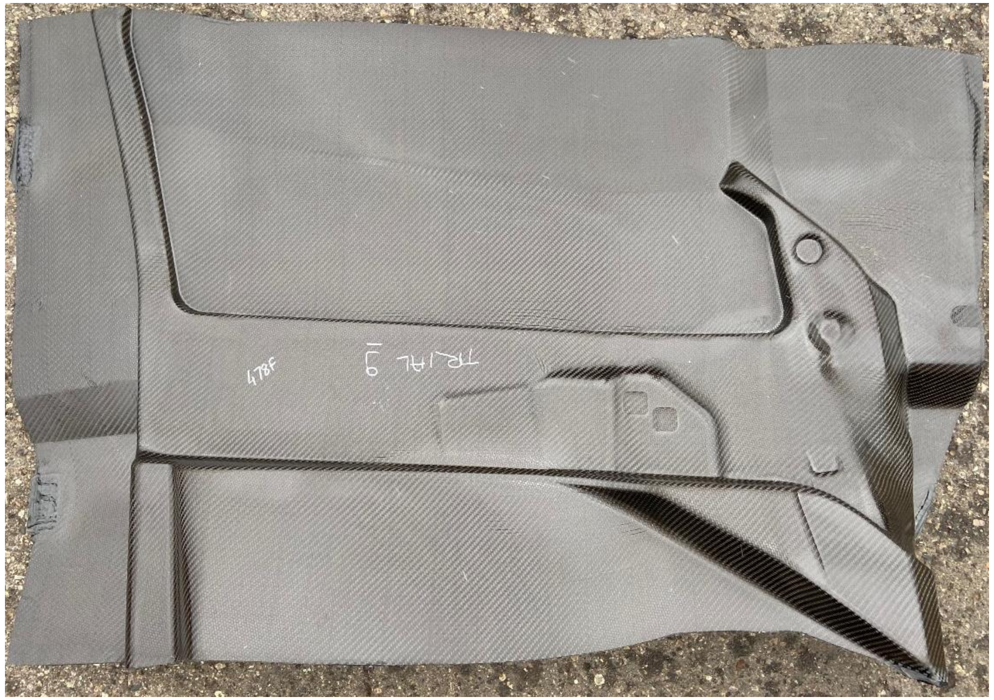
- Window, sash formation through use of cavity driver
- Door handle region formation through use of a smaller cavity driver
- Adjustable slots to vary material holding locations
- A simple A-frame with needle gripers is being considered

Design changes, cavity driver location and deployment guided by manufacturing to response simulations

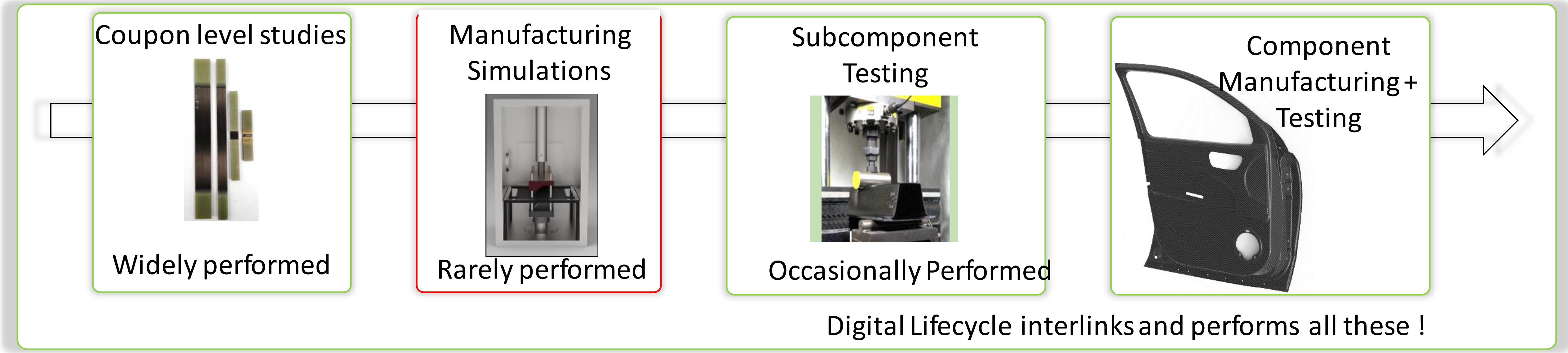
Composite Parts

Inner Beltline Stiffener

Inner Panel



Concluding Remarks



Coupon level studies

Widely performed

Manufacturing Simulations

Rarely performed

Subcomponent Testing

Occasionally Performed

Component Manufacturing + Testing

Digital Lifecycle interlinks and performs all these !

- Digital Lifecycle presents a comprehensive scalable platform to enable the design and manufacturing the world's first thermoplastic composites door !!!
- Systematic experimental evaluation of different material preforms were crucial inputs for the Digital Lifecycle Process.
- Subcomponent verification served as a crucial milestone for Digital Lifecycle and helped the team take crucial decisions.

Team and Acknowledgements

- **Dr. Srikanth Pilla (PI)**
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- Dr. Shridhar Yarlagadda (Co-PI)
- Duane Detwiler (Co-PI)
- Ryan Hahnlen (Co-PI)
- Dr. Paul Venhovens (Faculty)
- Melur (Ram) K. Ramasubramanian (Faculty)

Design Team

- Aditya Yerra, Alireza Zarei, Amit Deshpande, Lukas Fussel

Manufacturing Team

- Sai Aditya Pradeep, Amit, Sushil, Ashir, Senthil, Akash
- David, Rick, Gary, Edward and Nick (Staff)

FEA Team

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- Istemi Ozoy, Bazle Haque, Laxmanan

Material Supplier and Draping Analysis:

- Pal Swaminathan

Cost Team

- Pardhvi Shah, Gaurav Dalal

Tooling Team

- Bruno Mariani, Mike Tabbert, Dave, Rob, Mike

OEM Team

- Skye Malcolm

Students Graduated

6 PhD Students
7 Masters Students

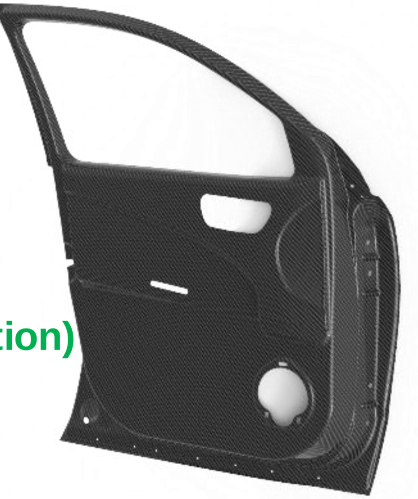
The team is thankful for the financial support from the Department of Energy, Project # DE-EE0007293 and Program Managers Felix Wu and David Ollett

Summary

Baseline Door

Structural Parts	**17 Parts**
Structural Mass	**15.44 kg**
Total Parts	**61**
Total Mass	**31.1 kg**
Trim + Glazing	**3.7 kg + 3.49 kg**
Performance	**5 star**
Costs ($/lbs saved)	**NA**

Ultralightweight Composites Door



Structural Parts	**6 Parts**
Structural Mass	**8.4 kg**
Total Parts	**52**
Total Mass	**21.1 kg**
Trim + Glazing	**2.59 kg + 1.34 kg**
Performance	**Meets or exceeds (Simulation)**
Costs ($/lbs saved)	**$ 5.8 ($ 5 permitted)**
	$ 1.92 (LCCF Door)

- Manufacturing completed for Inner Beltline Stiffener and Inner Panel
- FEA showed the composite door exceeding static and crash targets.
- Assembly of Doors are currently underway
- Crash tests performed and targets exceeded
- Cost analysis was updated.