Functionally Designed Ultra-lightweight Carbon Fiber Reinforced Thermoplastic Composites Door Assembly

Project ID: mat118

DOE Vehicle Technologies Office Annual Merit Review, Online, June 21 - 25, 2021

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

Overview

Timeline

- Start: December 1, 2015
- End: November 30, 2021
- 90 % Complete

Budget

- **Total project funding**
  - $2,249,994 (DOE)
  - $3,117,759 (Cost-share)
- **Funding for Budget Period 1 (12/1/2015 - 1/31/2017)**
  - $642,819 (DOE)
  - $871,357 (Actual Cost-share)
- **Funding for Budget Period 2 (2/1/2017 - 01/31/2018)**
  - $624,023 (DOE)
  - $674,889(Actual Cost-share)
- **Funding for Budget Period 3 (2/1/2018 - 01/31/2019)**
  - $643,239 (DOE)
  - $846,747(Actual Cost-share)
- **Funding for Budget Period 4 (2/1/2019 - 11/30/2021)**
  - $ 339,913 (DOE)
  - $ 773,906 (Actual Cost-share)

Barriers

- **Cost/Performance**
  - High cost of CFRP is the greatest barrier to the market viability of advanced composites for automotive lightweight applications.
  - Meeting CFRP-Thermoplastics performance to satisfy/exceed fit, function, crash and NVH at desired cost.
- **Predictive tools**
  - Integration of predictive models between systems (design/geometry/process/analysis) and at all length scales.

2017 USDRIVE MTT Roadmap report, section 5.1 and USDRIVE Partnership Plan, Goal 4, August 2020

Core-Partners

- Clemson University
- Honda North America
- Proper Tooling
- Lanxess
- University of Delaware

Relevance: Project Objectives

1. **Achieve a 50% weight reduction (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)

Milestones

- ✓ Establish design criteria (FY 2015-2016)
- ✓ Develop a detailed target catalogue (FY 2015-2016)
- ✓ Create a test and evaluation plan (FY 2015-2012)
- ✓ Benchmark the current door (FY 2015-2016)
- ✓ Test and catalogue commercially available materials (FY 2015-2016)
- ✓ Design and develop three functional door concepts that can meet project targets. (FY 2015-2016)
- ✓ Design optimization for non-linear load cases (Crash requirements) (FY 2017-2018)
- ✓ Down select design concept for concept detailing (FY 2016-2017)
- ✓ Design optimization for linear load cases (Use and misuse) (FY 2016-2018)
- ✓ Design optimization for non-linear load cases (Crash requirements) (FY 2018-2019)
- ✓ Fit and function testing with thermoset prototype door(FY 2018-2019)
- ✓ Sub-component testing (FY 2019 Q3)
- ✓ Final cost estimation (FY 2019 Q4)
- ✓ Design release for tooling (FY 2020 Q1)
- ✓ Tooling design completed (FY 2021 Q2)
- ✓ Started - Tool manufacturing (FY 2021 Q2)

COVID 19

- ⃠ Not Started - Prototype manufacturing (FY 2021 Q3)
- ⃠ Not Started - Final door crash testing (FY 2021 Q3)

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

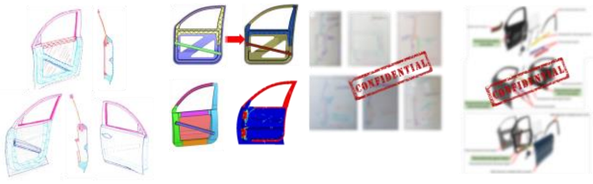
$$\begin{Bmatrix} f_1 \\ V_1 \\ M_1 \\ f_2 \\ V_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 & 0 & -\frac{AE}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{AE}{L}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

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

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

Phase 2

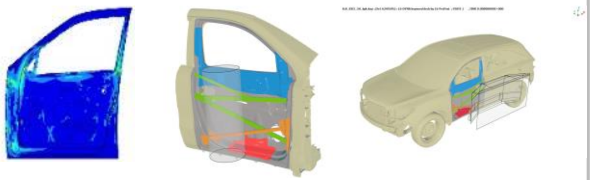
Concept Development



Extensive concept development
Systems level approach
Aggressive parts consolidation

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

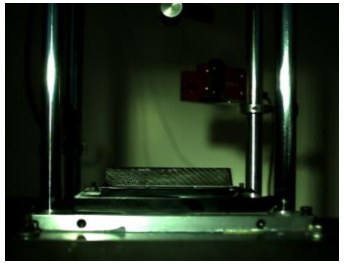
FEA Simulations



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

Phase 3

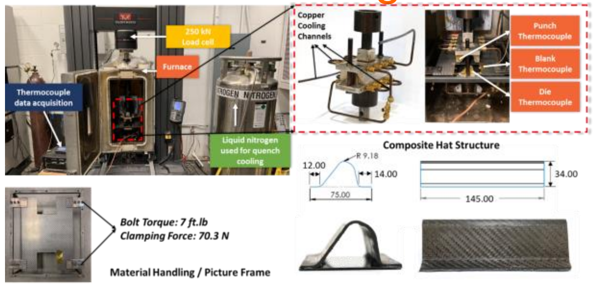
Subcomponent Testing



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

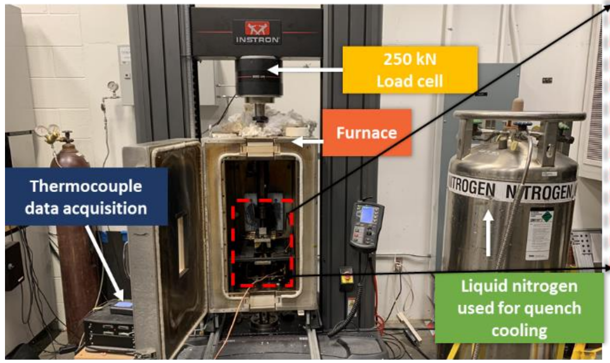
Leveraging experience of suppliers like Proper Tooling + Lanxess

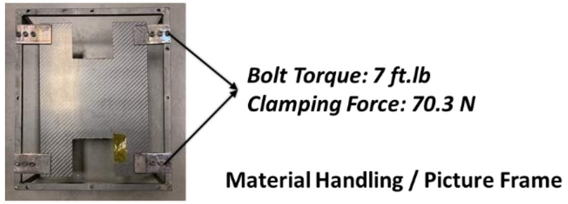
Currently in last phase of project

Testing

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

Progress: Manufacturing & Simulations



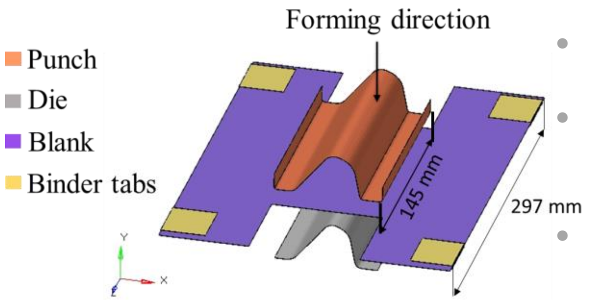


Material Handling / Picture Frame

Composite Hat Structure

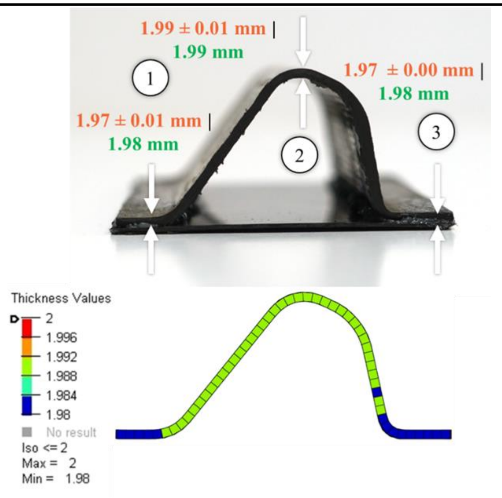
First tool to incorporate copper cooling channels for liquid nitrogen in order to quench cool a geometrically complex formed component!

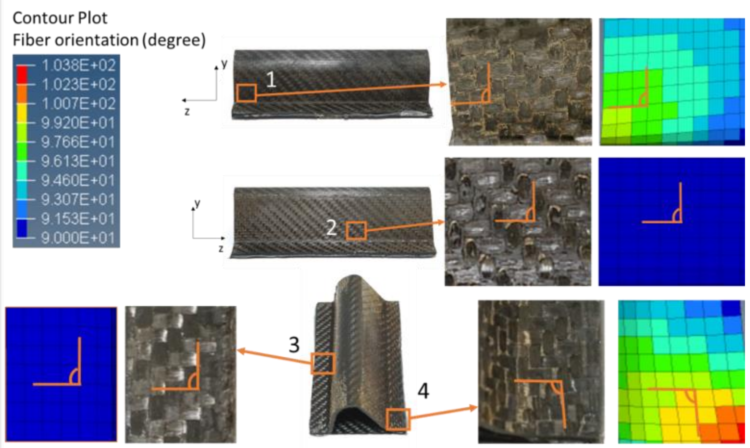
Simulation Setup



- **Solver:** RADIOSS
- **Material model:** RADIOSS MAT LAW 58, anisotropic hyperelastic fabric
- **Element type:** fully integrated QBAT shell elements, Mesh size: 2mm

Thickness Variation	Fiber Orientation



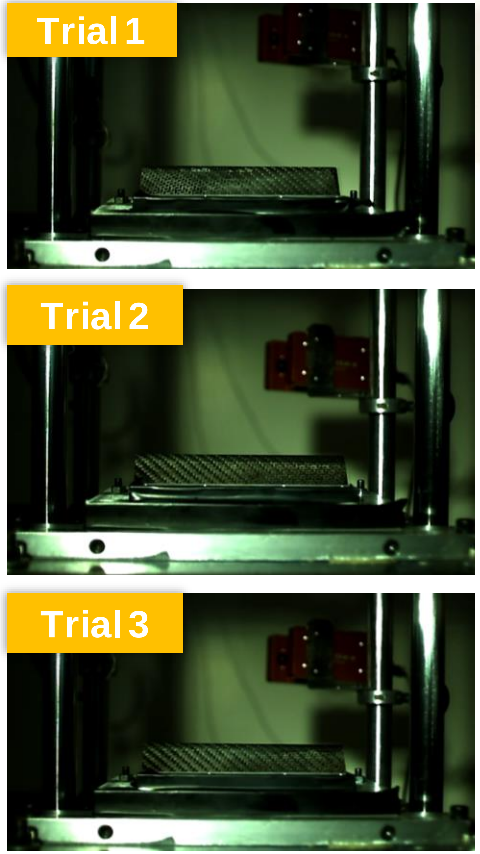


Location	Experimental Average (°)	Std.	Simulation	%Difference
1	96.76	1.42	95.77	1.02
2	91.90	3.19	90.18	1.87
3	90.93	0.81	90.00	1.03
4	100.08	5.17	96.72	3.36

A comparison between the experimental thickness and fiber orientation with the simulated prediction shows very good agreement !!!

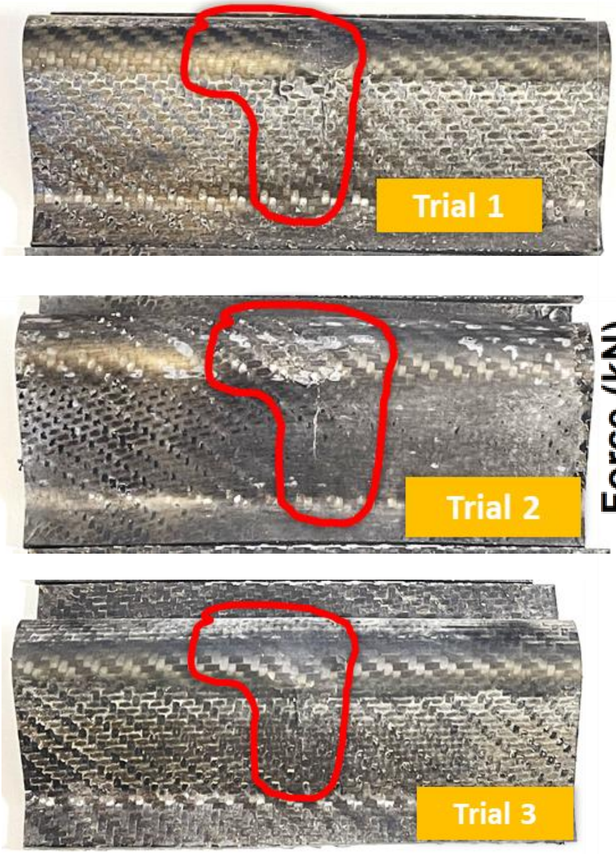
To the best of the team's knowledge this is the **first synergistic experimental and numerical approach** that ***wholly captures process induced effects and its impact on static and dynamic mechanical performance.***

Progress: Subcomponent Testing

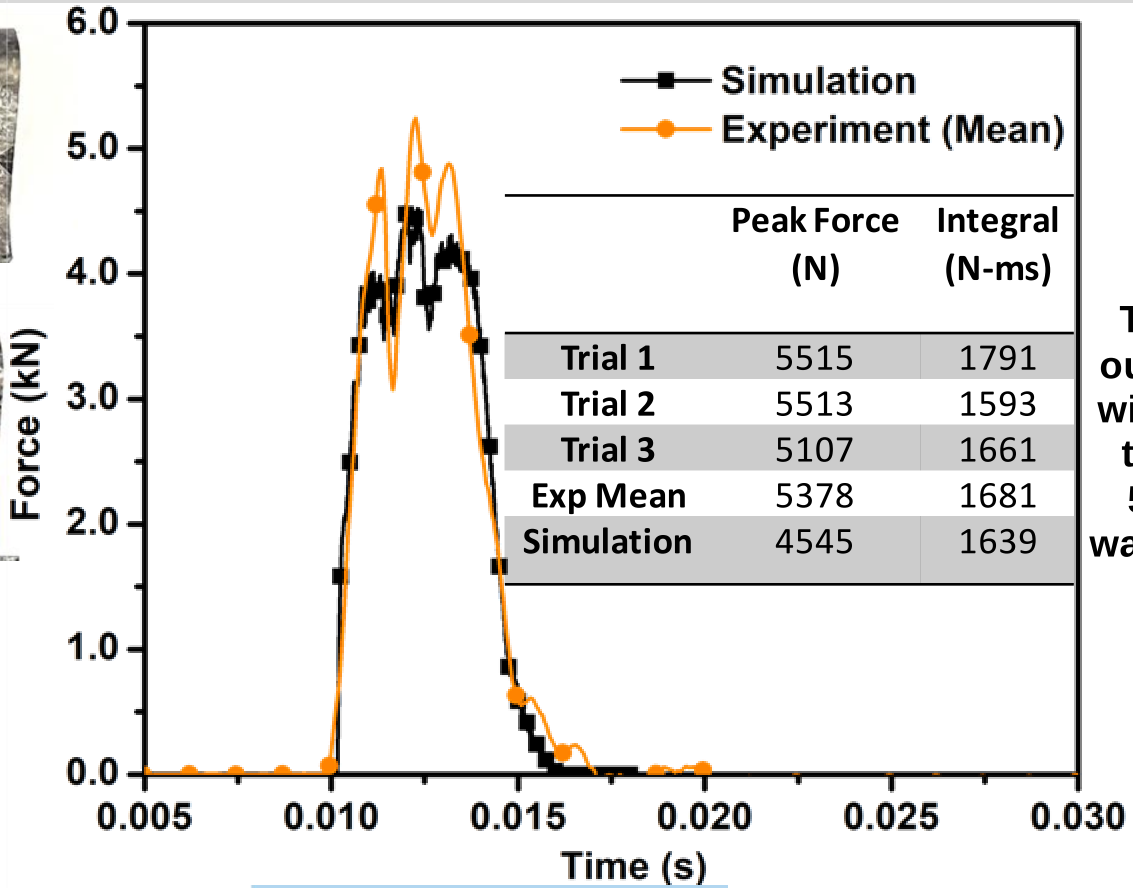


Impact testing

Impactor diameter: 1 in
Impactor weight: 3.1 kg
Initial velocity: 4.3 m/s
Energy: 28.65 J

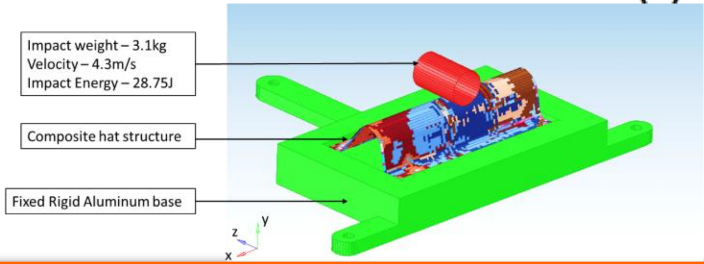


Max Hat deflection: **18.90 mm**
Max Spine deflection: **6.36mm**
Peak Load: **5514.18 ± 235 N**



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

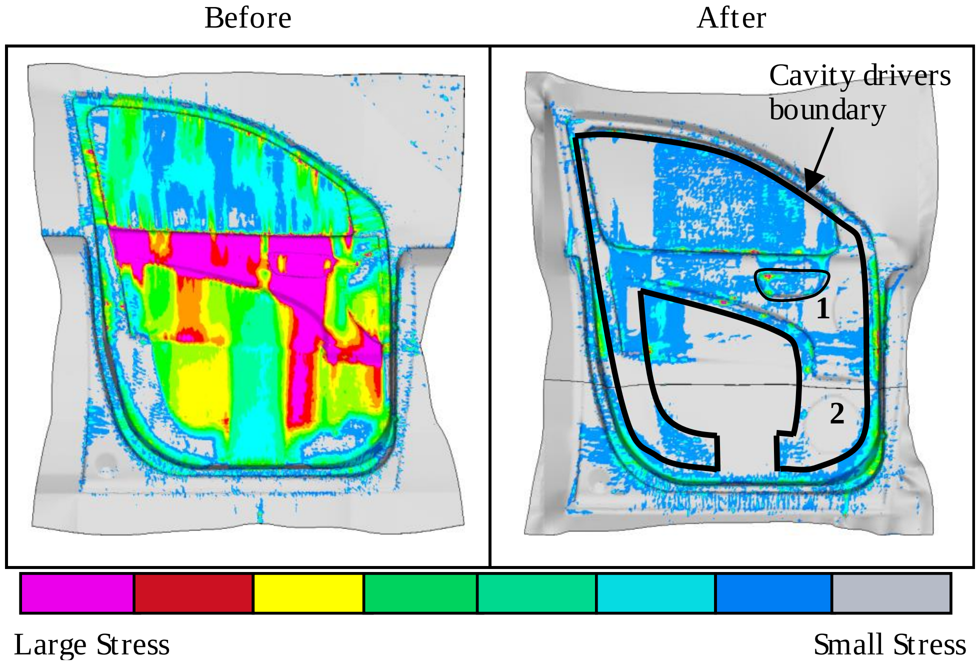
Test was carried out in accordance with the simulated test conditions. 5mm mesh size was used in full car simulations

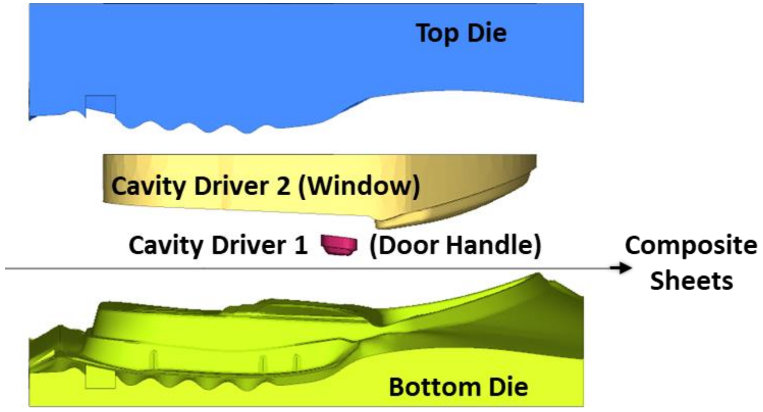


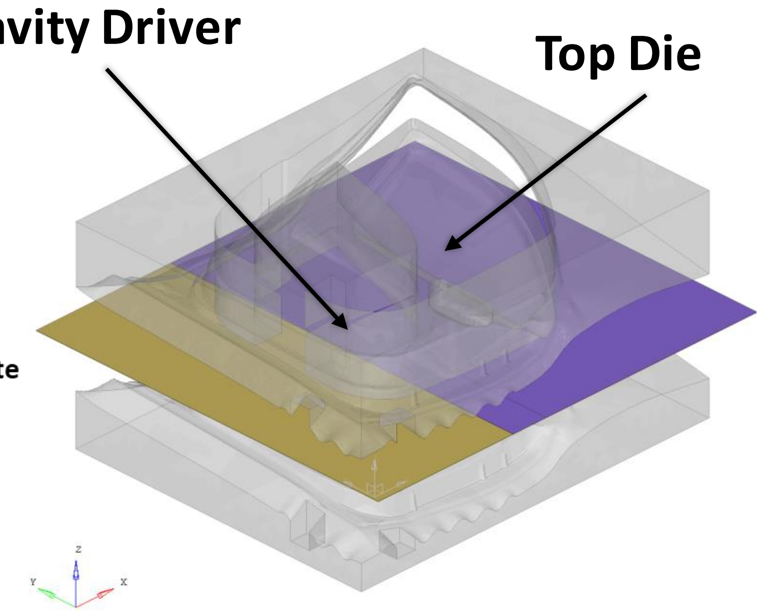
Software: LS-Dyna
Material model: LS-DYNA material law MAT 54
Damage mechanics: Chang-Chang failure model

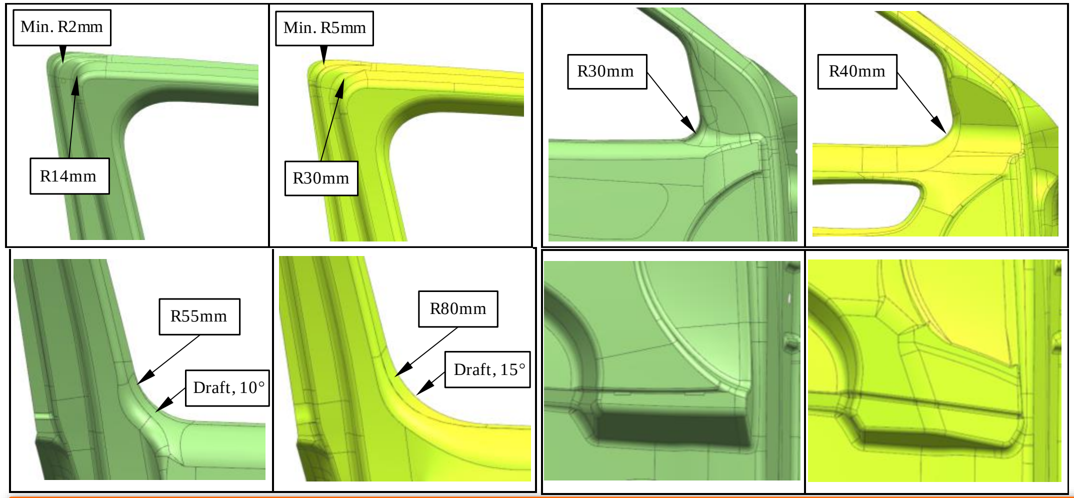
A comparison between the experimental results and the simulated prediction shows good agreement.
The damage behavior is consistent with the experimental results.

Progress: Manufacturing Simulation









- 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

Progress: Concept Development: Final

World's First Thermoplastic Composites Door !

Design Innovation: *Parts consolidation*
Technology Innovation: *Strategic use of materials (composites + metals) based on FEA and manufacturing simulations*

Structural Components

Inner frame
- **Manufacturing:** *Thermoforming*
- **Material:** *PA 6 + 50 % wt. Woven CF*

Anti-intrusion beam assembly
- **Manufacturing:** *Hot Stamped and Welded*
- **Material:** *Ultra high strength steel*

Inner beltline stiffener
- **Manufacturing:** *Thermoforming*
- **Material:** *PA 6 + 50 wt % Woven CF*

Outer beltline stiffener
- **Manufacturing:** *Extrusion and Welded*
- **Material:** *Aluminum 6061*

Lower Reinforcement
- **Manufacturing:** *3D Printing Dies + Stamping*
- **Material:** *Aluminum 6061*

Aesthetic Components

Design Innovation: **Elimination of conventional trim by integrating trim components as snap fits !**

Manufacturing: *3D printing*

Baseline Trim Weight: 3.49 kg
Snap fit Trim Weight: 1.34 kg

Baseline Door Structural Parts: 17 Parts
Composites Door Structural Parts: : 6 Parts

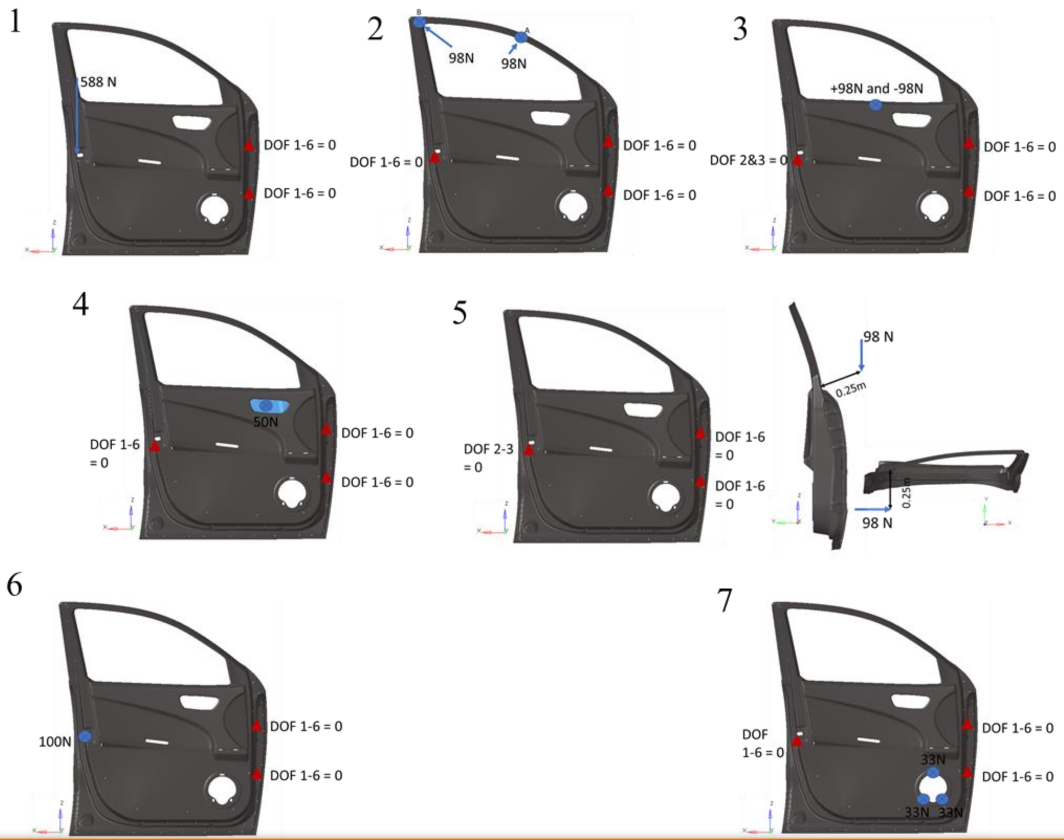
64 % Parts Consolidation

Baseline Door Structural Mass: 15.44 kg
Composites Door Structural Mass: 8.4 kg

45 % Weight Reduction

Progress: Static Performance

- The linear static load cases represent door performance for daily use and occasional misuse
- The composite design optimization is carried out for the listed static load cases.
- All static load cases are well satisfied for the composite door.



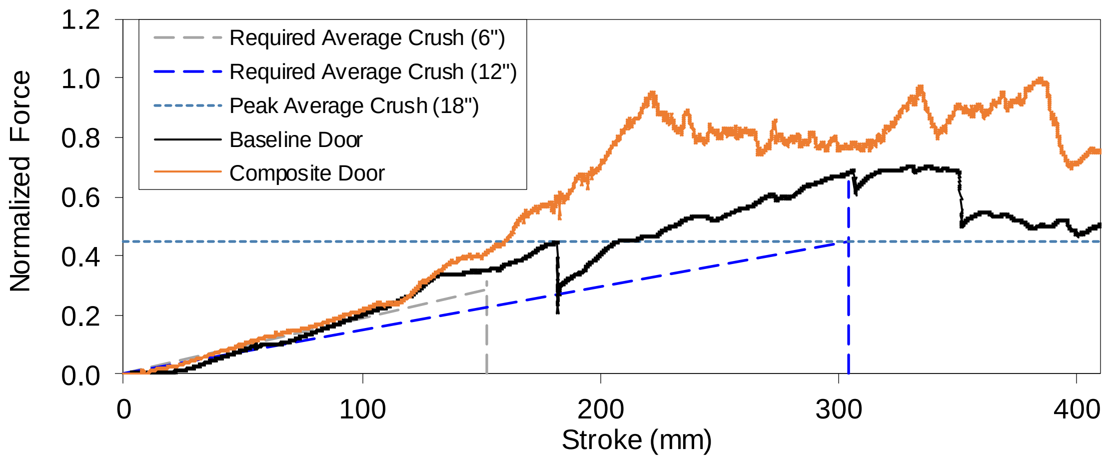
S No.	Target category Subcase		Composite door response
A	Mass Target (% mass savings)		
1		Structural frame mass	45%
2		Total mass	32%
B	Frame Related (% stiffness increase)		
1		Door Sag - Fully open	32%
2a		Sash Rigidity at point A	10%
2b		Sash Rigidity at point B	55%
3		Beltline stiffness-Inner panel	79%
4		Window regulator (Normal)	69%
5a		Mirror Mount rigidity in X	1%
5b		Mirror Mount rigidity in Y	67%
6		Door Over opening	1%
7		Speaker mount stiffness	48%
8		Outer panel stiffness	80%

The prototype composite door satisfy all static load cases
with more stringent target definitions set by the OEM partner.

Progress: Structural Performance

FMVSS 214 S Quasi-static Pole test

- A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.



FMVSS214 S OEM Requirements	Composite door response (% Improved)
Initial Average Crush	23%
Intermediate Average Crush	104%
Peak Crush	124%

IIHS Side Impact moving deformable barrier test

- A moving deformable barrier of mass 1500 kg is impacted with a stationary vehicle at 50 km/h.
- A 5th percentile female SID IIs dummy is included in the test as per NCAP guidelines.
- A gauging metrics for IIHS SI- MDB is defined
  - Success (Green) – If intrusion is below baseline target values (<b)
  - Tolerable (Yellow) - If intrusion is more than baseline values but smaller than 10 % difference (>b, <b+10%)
  - Failure (Red) – If intrusion is 10% above baseline value (>b+10%)
- No exposed crack in the door interior.

Key Performance Indicator	Composite door response
Safety survival space	+4%
Max roof intrusion	- 4%
Max windowsill intrusion	-14%
Front door dummy hip intrusion	-22%
Max door lower intrusion	-1.5%

The average crush resistance of composite door is significantly higher than the OEM requirements for QSP test.
The composite door outperforms baseline door for IIHS MDB test with No exposed crack.

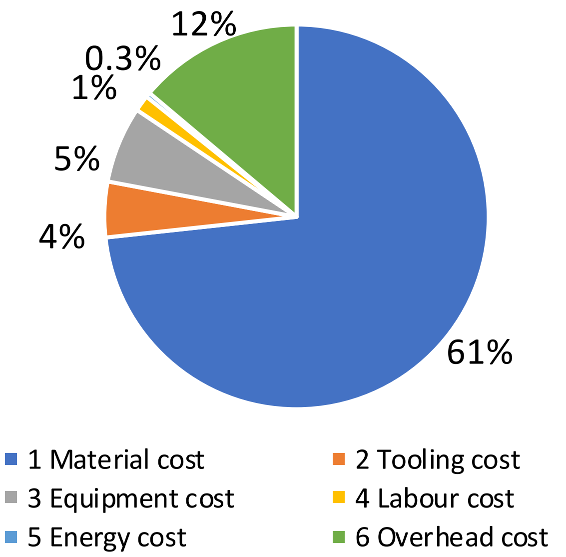
Progress: Cost Modelling

Parametric cost model assumptions:

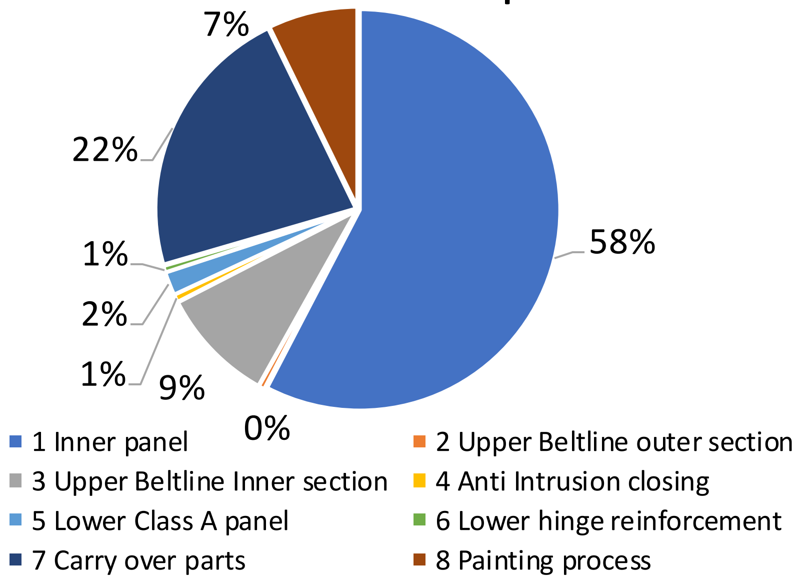
- Production volume per year – 20,000
- Workers per machine – 4
- Overhead rate (18 ~ 24% of total cost)
- Cost of carry over parts is constant (~ $180)
- Cost of carbon fiber > **$ 7/lb**

Parts	Baseline Weight (kg)	Current Composite Design	
		% Mass reduction	$$/lb. saved
Structural parts	15.44	45%	4.44
Non-structural parts	9.37	47%	4.18
Carry Over Parts	6.29	0%	0
Painting			
Total	**31.1**	**32%**	**5.84**

Cost based on production factors (%)



Cost based on door components



Identified parameters	Identified Variations	Total Cost ($)
Electricity cost per kWh(cents)	7.5~17	813 ~954
Scrap rate(%)	4~15	
Mold life(years)	6~11	
Equipment life(years)	5~13	
labor wage($)	15~28	
Material cost per kg ($)	105~119	

Cost Modelling: Glass vs Carbon

	Carbon fiber door	LCCF Door (Oakridge)	Glass fiber door
Light-weighting	32 %	32 %	>25 %
Static Performance	Excellent	NA	Satisfactory (Validated MAT card used)
Dynamic Performance (QSP test)	Excellent	NA	Excellent (Validated MAT card used)
Cost of Inner Panel	**$ 570**	**$ 494**	**$ 74**
Total Cost of door (with parts consolidation)	**$ 928**	**$ 842**	**$ 352**
Target cost increase per lb. saved	**$ 3.76**	**$ 3.76**	**$ 2.94**
Achieved Cost increase per lb. saved	**$ 5.84**	**$ 1.92**	**0**

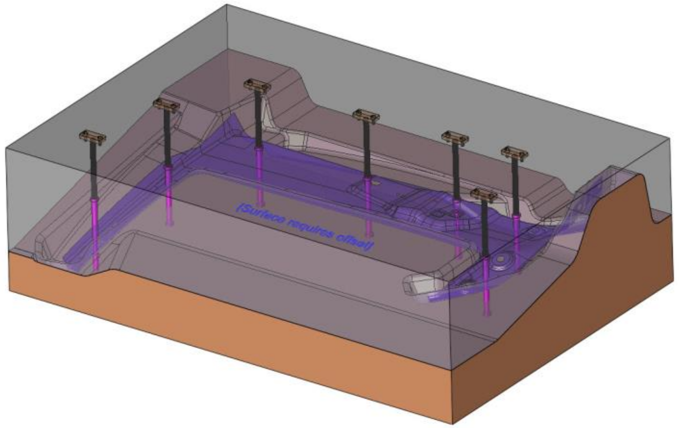
- ❑ Cost of carbon fiber is > $ 7/lb.
- ❑ Low cost carbon fiber is $ 4.75 /lb
- ❑ Glass fiber cost < Cost of carbon fiber

The Current door design is optimized for Carbon fiber material. If optimized for Glass Fiber – almost 25% of weight savings could be achieved at approximately same cost as baseline steel door which successfully meets design requirements.

Progress: Manufacturing

Inner Beltline Stiffener	Inner Panel

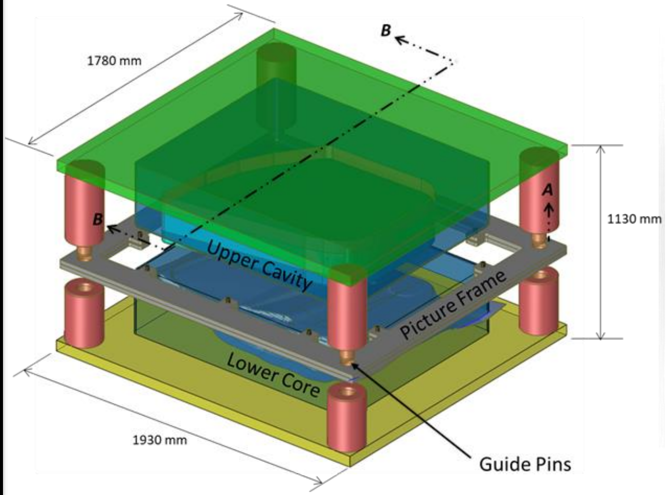
Inner Beltline Stiffener

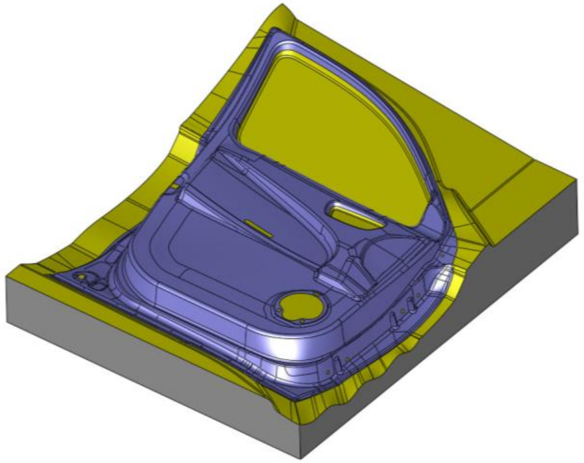


Compression Tool

- Tool Size: 1200 mm x 850 mm x 450 mm
- Tool material: Aluminum | B3 Finish
- Lead time: 8 weeks
- Rapid heating (150 °C) and cooling
  - Great for improving surface finish
  - Reduces Cycles Time

Inner Panel





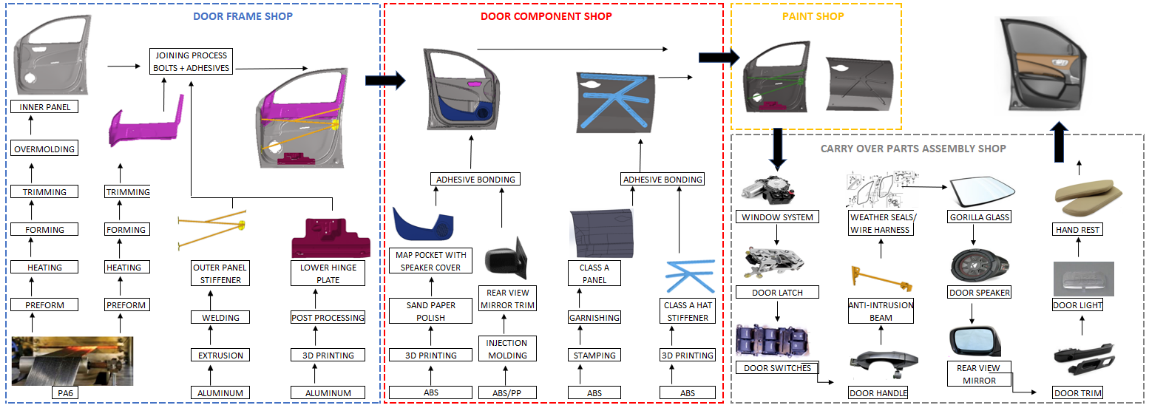
Compression Tool with 2 Cavity Drivers

- Tool Size: 1930 mm x 1780mm x 1130 mm
- Tool material: Aluminum | A2 High Polish
- Lead time: 14 weeks
- Rapid heating (150 °C) and rapid cooling
  - Great for Class A surface
  - Reduces Cycles Time

Response to Reviewer Comments

Comment from 2020 Annual Merit Review	Response
The four-phase approach addresses the major areas of automotive door design. The one shortcoming in the approach was having the material characterization plan based on flat plaque samples that repeatedly have been shown to be optimistic compared to material properties of shaped parts	The team's philosophy for this project has been the establishment of the manufacturing to response pathway that simulates a coupled forming and mechanical response. This was started from a coupon level and taken upto a subcomponent and component level. Subcomponent trials were performed on a hat section as shown below **(slides 6 & 7)** 
The research team is a partial victim of the COVID situation because current conditions on campus and within industry challenge progress. However, this is now into year five and molding tools have not yet become part of the program, which appears to be lagging. Nonetheless, progress on achieving goals related to design and manufacturing feasibility is noteworthy and commended. While the cost goal has not been met, the research team projects a cost penalty of \$5.40/lb of weight saved. It would be worthwhile to challenge the material suppliers—what carbon cost is needed to achieve the \$5/lb of weight saved target? Is this design feasible if one projects a carbon fiber cost of \$5.50/lb?	The cost of carbon fiber projected by LCCF (Oakridge) **4.75 \$/lb** would certainly suffice to achieve \$ 5/lb of weight saved. The design is extremely close to being feasible. We are marginally above \$ 5.50/lb at \$5.84/lb. With increased adoption from OEM's, material suppliers like Lanxess are willing to increase production which would lead to further drop in material costs.

Response to Reviewer Comments

Comment from 2020 Annual Merit Review	Response
Good progress has been made in the work. Techno-economic analyses of the final door production and cost seem to be missing, based on results from the authors' work, not on projections. Any supply chain issues have not been mentioned or addressed. The reviewer noted that the woven carbon fiber cloth was obtained from a supplier and inquired about how this is expected to affect final cost of the door. Is this supplier a sole supplier? If so, how might this affect tech-to-market transfer of this technology? The reviewer also noted that there is no word on durability of the carbon fiber laminates over time in component form.	While the reviewer is correct in citing the importance of supply chain issues, this was not part of our cost models and out of scope. We obtained pre-consolidated sheets from supplier for easier handlining. Currently there are multiple suppliers of this material. At the time of project initiation Lanxess was sole supplier. The tech-to-market transfer is the manufacturing to response (MTR) pathway that help OEM's and material suppliers evaluate coupled formability and mechanical response. Our material supplier Lanxess has similar materials in production of various OEM's that meet durability requirements
The research team appears to have its work cut out for them now. With the door design apparently complete, it is disappointing that work remains on tool and fixture design, but the payoff is in sight with a clear path forward toward composite thermoforming activities and door assembly. There appears to be no reason why this team should be unsuccessful molding and completing the door assembly and testing. It would be helpful for the researchers to step through the cycle time for primary operations to validate the 20,000-unit annual production rate goal.	Cycle time: The estimated cycle time for fabrication of single door in a single assembly line is 12.87 min. With 4 parallel assembly lines, the doors for 20,000 cars can be produced in approximately 179 days 

Remaining Challenges & Barriers

1. COVID 19

1) Talks with our tooling partners began August 2019. Tooling only began in May 2021

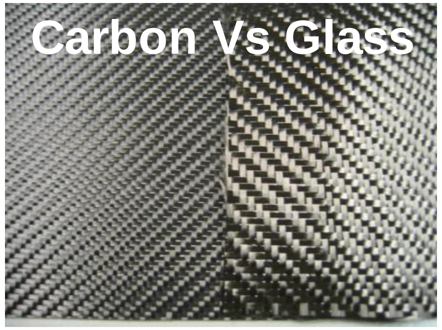
2) Currently Tooling is underway, but supplier was plagued with COVID related deaths.

2. Manufacturing

1) The team understands the challenges and barriers involved in manufacturing and assembly and is working tirelessly to chart to overcome these.

2) The team hopes to leverage experience gained from the manufacture & assembly of our previous low-cost prototype door.

3. Cost



1) The high cost of carbon fiber remains a barrier for cost targets.

2) Glass fiber woven composite door met most static targets.

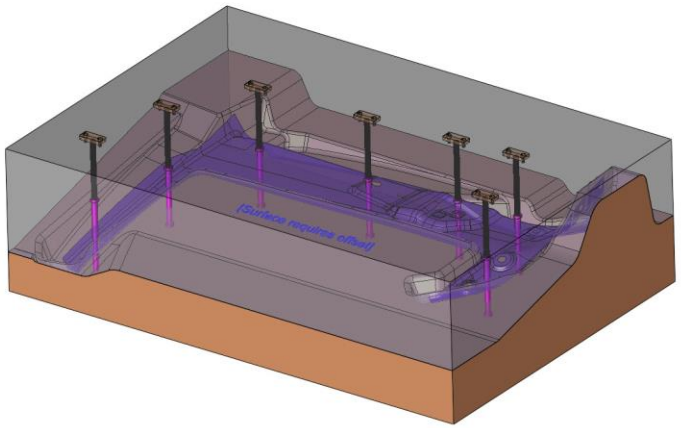
	CF	GF
Lightweighting	32 %	>25%
Material cost	X	1/10 x
Overall door cost	$ 928	$ 352
$/lb increase	$ 5.8	$ 0

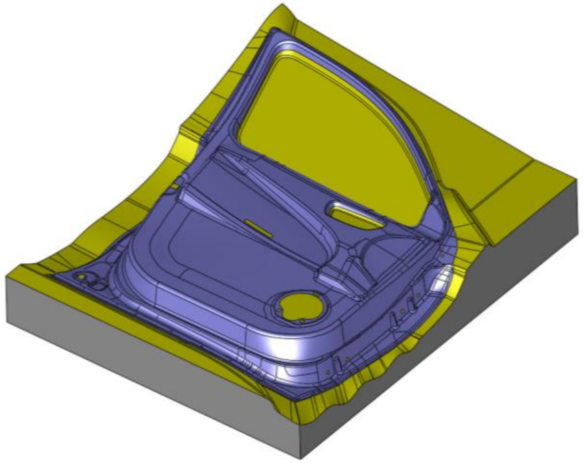
Collaborations

Key Organizations	Role	Responsibilities
Clemson University	Principal investigator	• Project management • Design development • Linear & NVH analysis • Cost & factory modeling • Discontinuous fiber material characterization
University of Delaware	Co - PI	• Non-Linear analysis • Continuous fiber (UD and Woven) material characterization • Design support
Honda The Power of Dreams	OEM Partner	• Target definitions • Student mentoring • Computation support for running complex simulations • Component & vehicle crash testing
LANXESS Energizing Chemistry	Material Partner	• Material Supplier • Manufacturing Simulation Support
Proper Group International Advanced Engineering • Superior Technology	Tooling & Prototyping Partner	• Manufacturing/tooling design & simulation • Prototyping

Proposed Future Work

Tooling + Manufacturing

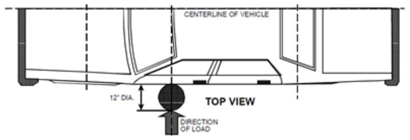




- Tooling: Currently underway at Proper Tooling
- Prototyping location is prepped and blocked off for trials
- Initial manufacturing trials for inner panel and inner beltline stiffener to be held in June and July 2021.

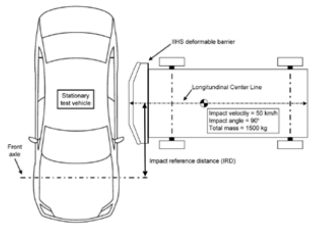
Testing

1. FMVSS 214s (Quasi-static pole test)



A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

3. IISH SI MDB(DB)



A moving deformable barrier is impacted with a stationary vehicle at 50 km/h.

Test	Composite Door Trials	Steel Baseline Trials
FMVSS 214s	2	-
OEM Test	2-3	2-3
IISH SI MDB	1	-

- Tests scheduled in August 2021

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

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

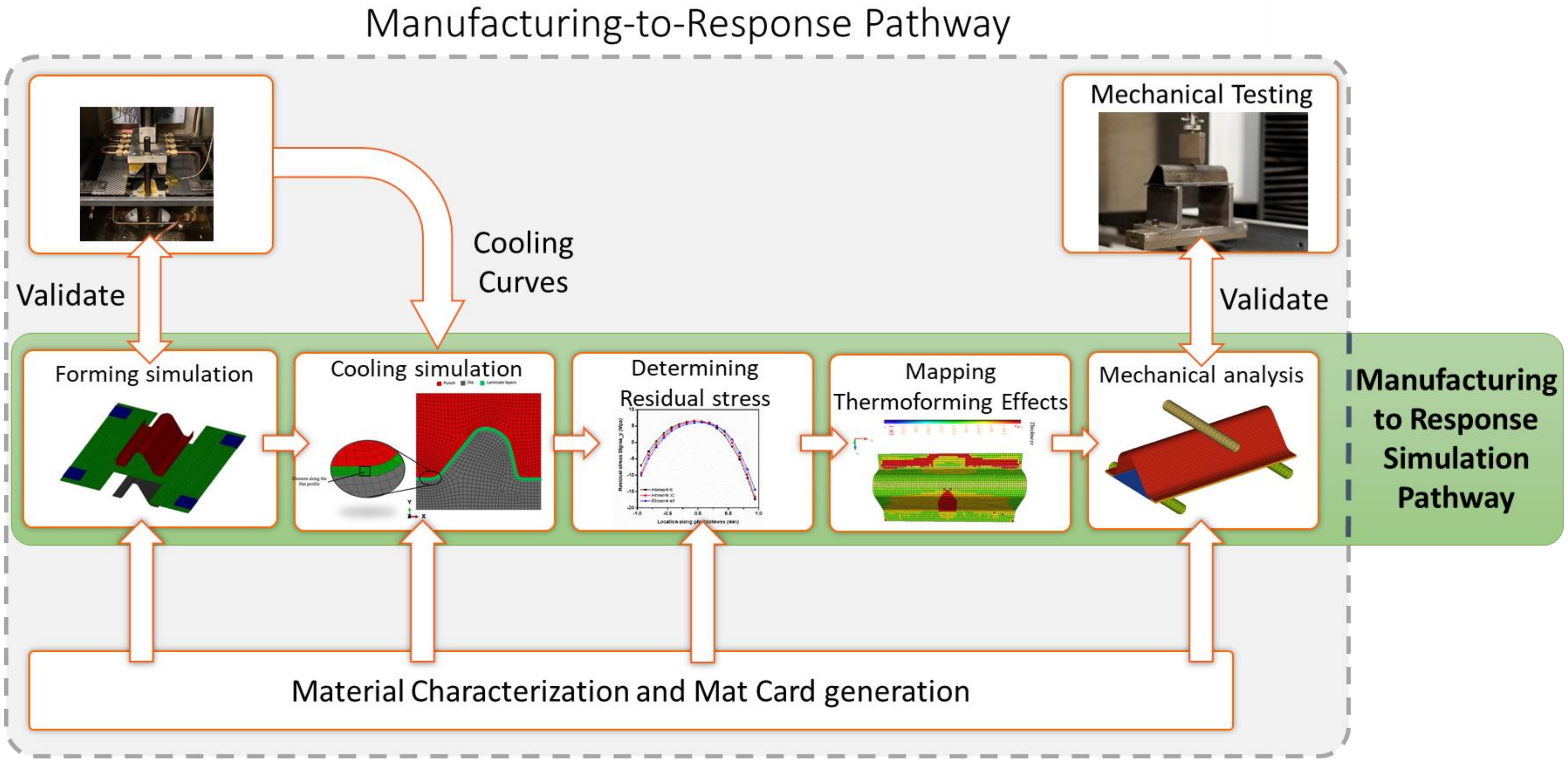
Structural Parts	**6 Parts**
Structural Mass	**8.4 kg**
Total Parts	**52**
Total Mass	**21.1 kg**
Trim + Glazing	**2.59 kg + 1.34 kg**
Performance	**Meets or exceeds (Simulation)**
Costs ($/lbs saved)	**$ 5.8 ($ 5 permitted)** **$ 1.92 (LCCF Door)**

- CAD modifications incorporating manufacturing inputs were undertaken.
- FEA showed the composite door exceeding targets.
- Tooling has reached advanced stages.
- Manufacturing trials scheduled in June and July 2021
- Crash tests scheduled in August 2021
- Cost analysis was updated.

2020 Technology Integration Award for Clemson Composites Center

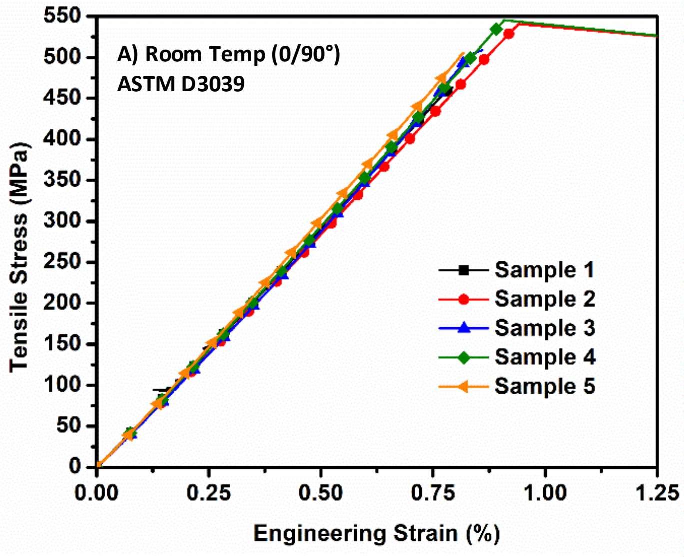
Technical Back Up Slides

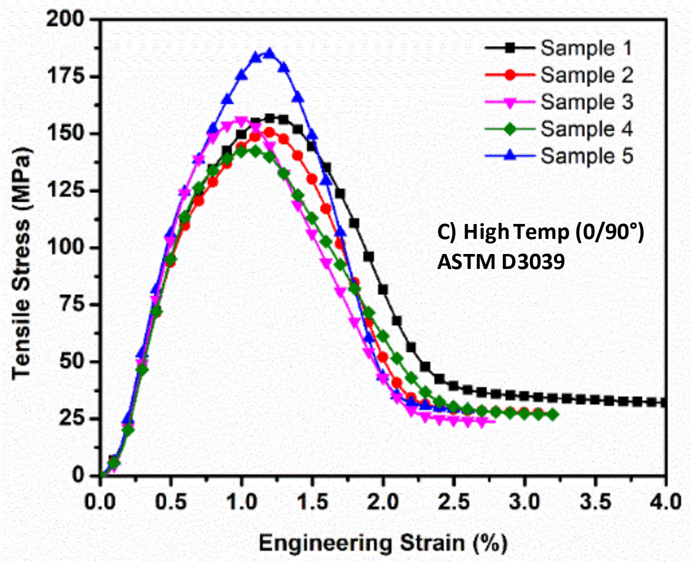
Manufacturing to Response Pathway



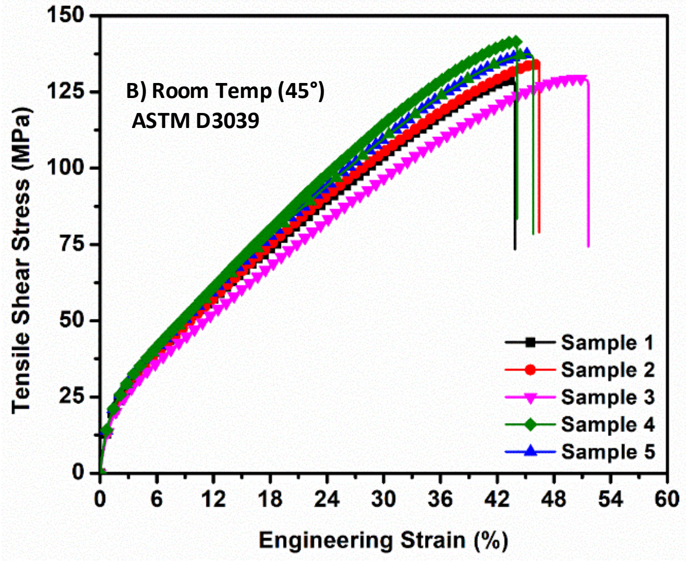
- Compared to other approaches the present work establishes a complete pathway for end-to-end analysis of thermoformed continuous carbon fiber reinforced Polyamide 6 (PA6) composite structure.
- To the best of the authors knowledge this is the **<u>first synergistic experimental and numerical approach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

Experimental Data





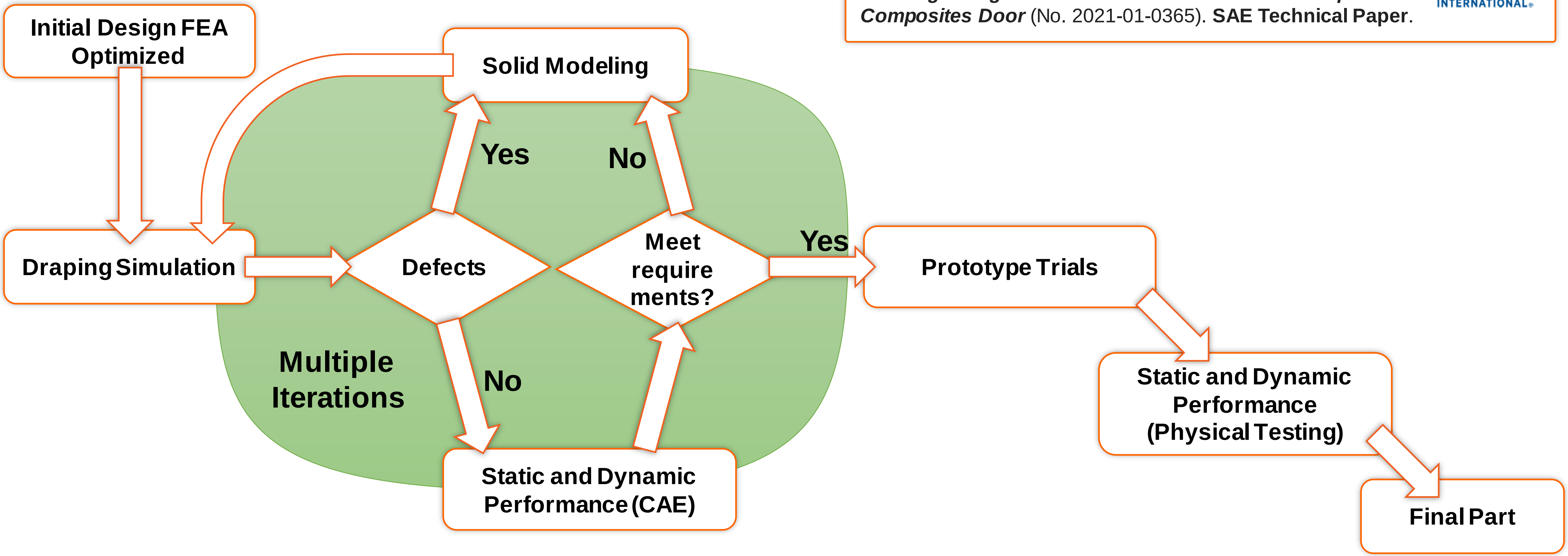
Property		Carbon/PA6
Specific Heat $[J/kg\ K]$ ASTM E 1269	@ 25°C	1206.65 ± 24.57
	@ 45°C	1304.96 ± 21.36
	@ 60°C	1364.76 ± 18.64
Thermal conductivity $[W/m\ K]$		0.682 ± 0.001



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

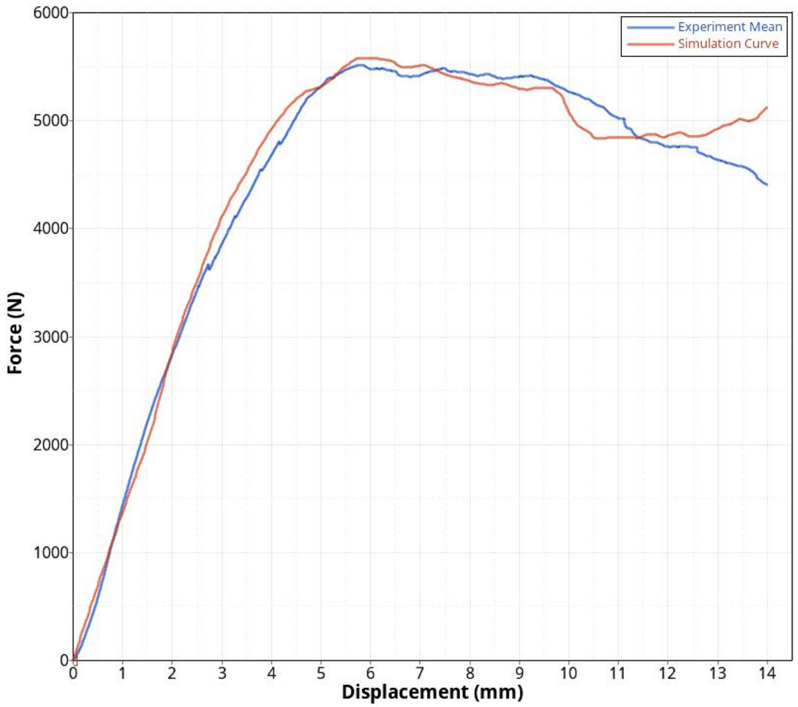
Manufacturing Simulations: Inner Panel

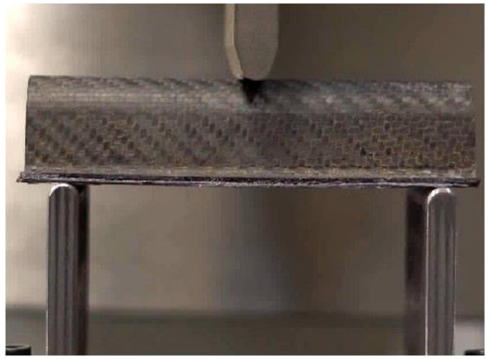
Mittal, A., Kothari, A., Pradeep, S. A., Savla, S., Limaye, M., Li, G., ... & Detwiler, D. (2021). ***Designing a Production-Ready Ultra-Lightweight Carbon Fiber Reinforced Thermoplastic Composites Door*** (No. 2021-01-0365). **SAE Technical Paper**.

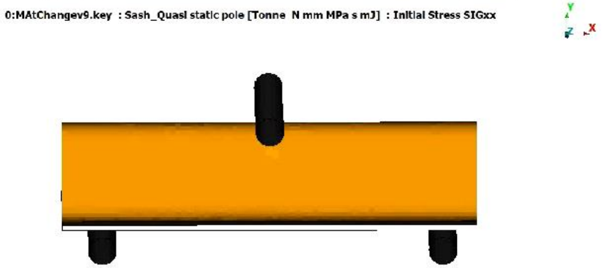


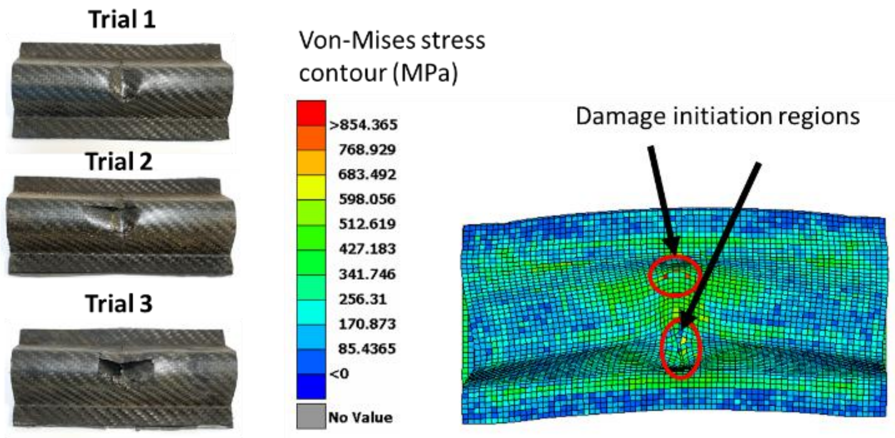
Design optimization for reduction of manufacturing defects using draping simulations with support from Lanxess

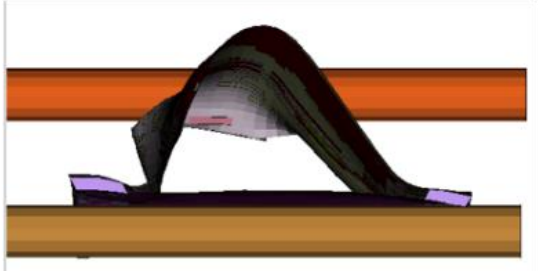
Model Validation: Quasi Static Performance









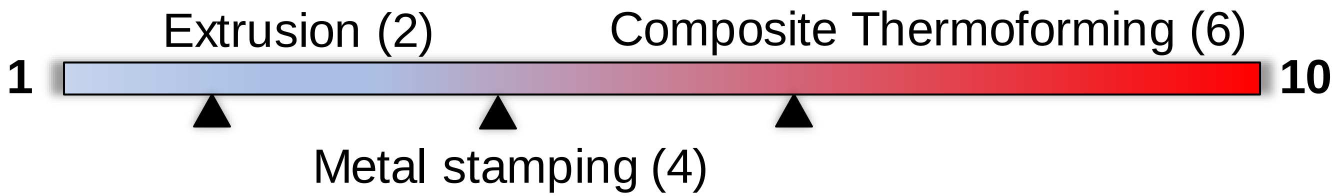


- A comparison between the experimental results and the simulated prediction shows good agreement.

- The damage behavior is consistent with the experimental results.

Qualitative Cost Model: Part Consolidation

Relative cost scale
Range = 1-10



	Baseline design/door	Composite design/door	Relative cost	Cost Benefits for n parts
Stamping	**16**	**2**	**4**	**88%**
Thermoforming	**0**	**2**	**6**	**-**
Extrusion	**1**	**2**	**2**	**50%**
Total relative cost for n parts	**64+0+2=66**	**8+12+4=24**		**63%**

Based on Qualitative inputs from Honda, Lanxess and Proper Tooling

- Only Manufacturing process costs considered here for the part consolidation cost comparison.
- Significant cost benefit (63%) ascertained qualitatively for the Composite door design as a result of tool consolidation into 6 structural components vs 17 components of baseline design
- A quantitative estimate of the cost benefit due to part consolidation is **$ 851,000.**