Finite Element Analysis and Performance Evaluation of an Ultra-lightweight continuous Carbon fiber thermoplastic composite door assembly

Project ID: mat118

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Clemson University

Outline

- Grand challenge
- Target definition and design approach
- Computational analysis and performance evaluation
- Manufacturing-to-performance pathway
- Design modifications based on manufacturing considerations
- Conclusion

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

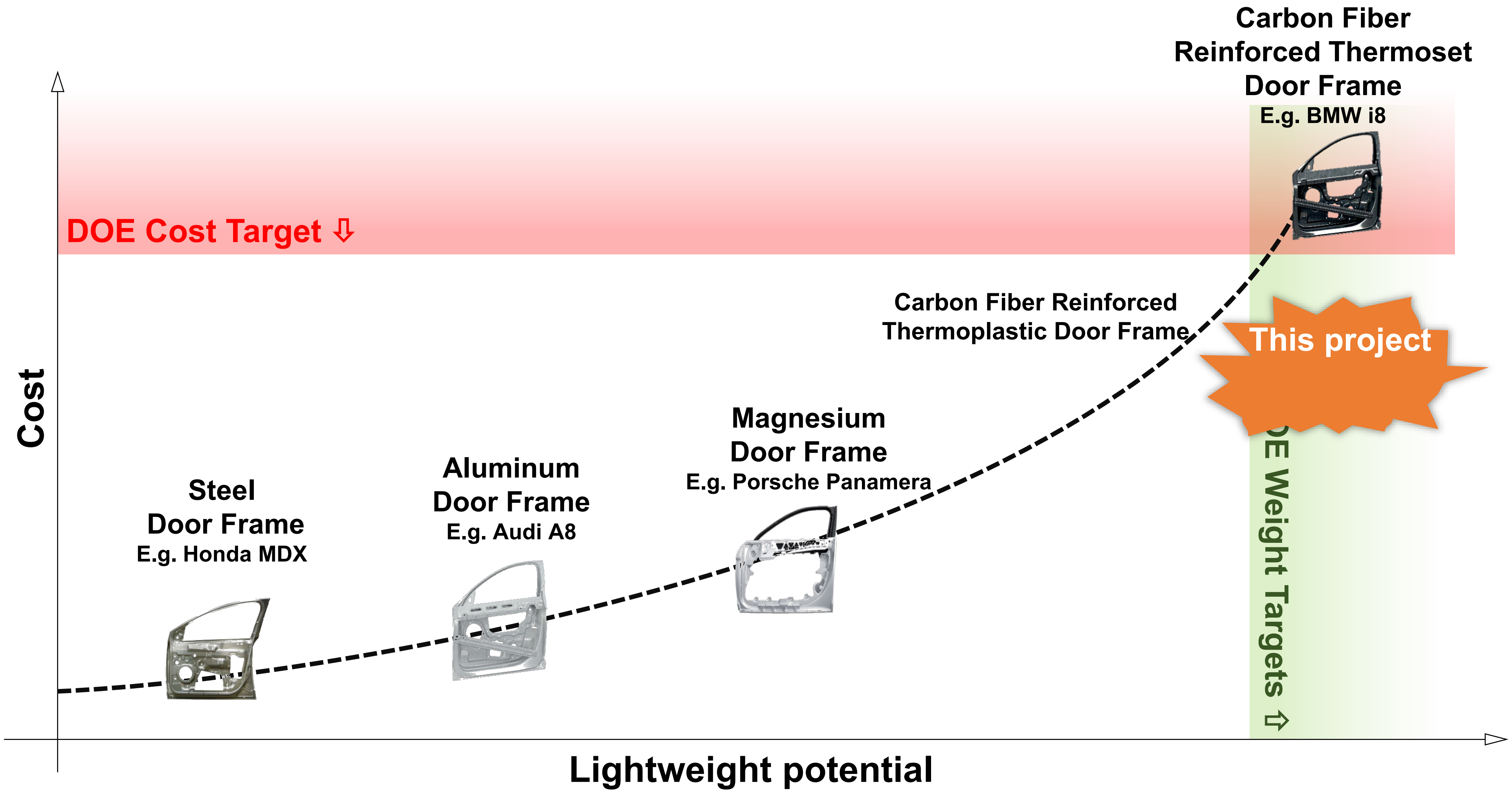
3. **Maximum cost induced is 5$ per pound saved**
   - Allowable increase = **$ 150.1 per door**

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

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

Target Definition: Big Picture

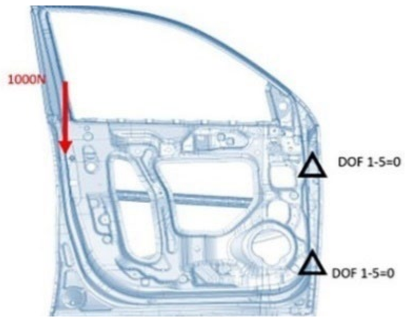
Benchmarking other lightweight door concepts and understanding performance vs cost tradeoffs.



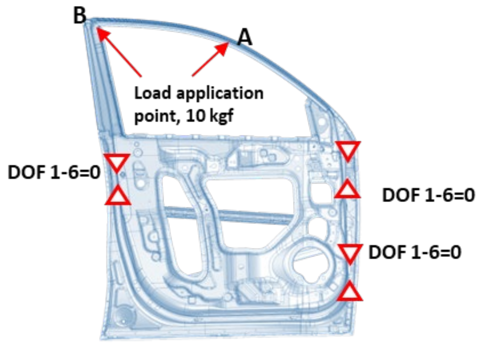
Target Definition: Design Requirements

Static load Cases

a. Door sag (DS)
b. Door sash (A and B)
c. Door over opening
d. Beltline stiffness
e. Mirror mount rigidity
f. Speaker mount stiffness
g. Door handle pull rigidity
h. Map pocket pull rigidity
i. Window regulator (figure not displayed here)



(a)



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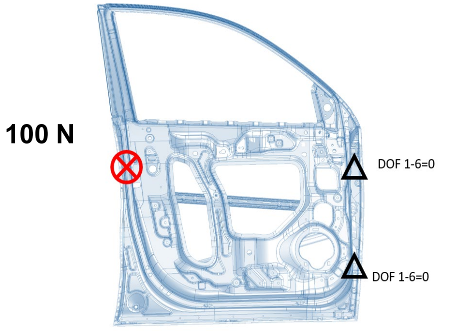
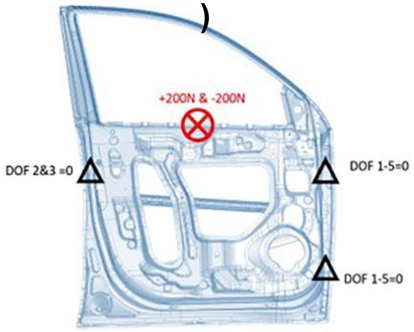


(c)



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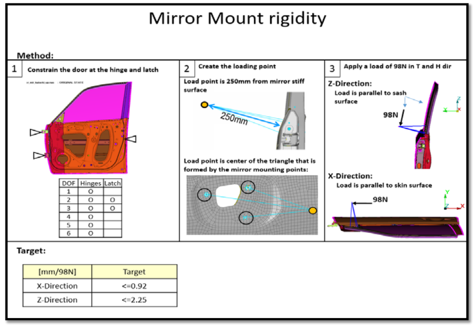
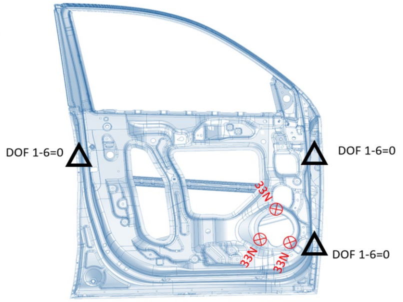


DOF	Hinges	Latch
1	O	
2	O	O
3	O	O
4	O	
5	O	
6	O	

[mm/98N]	Target
X-Direction	<=0.92
Z-Direction	<=2.25

(e)



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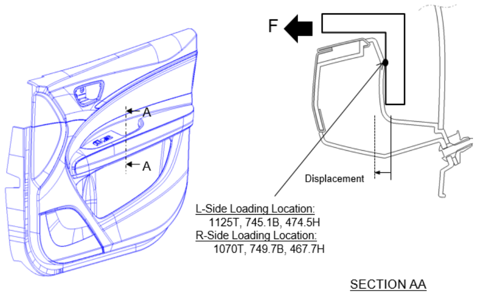
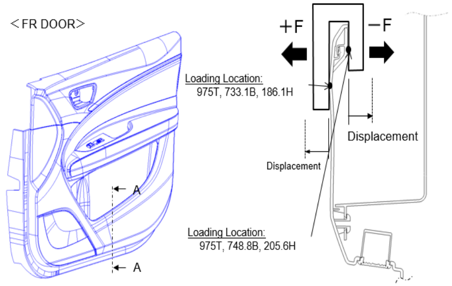


(g)

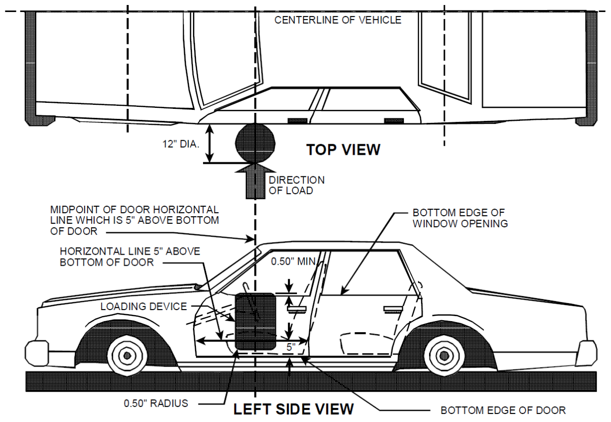


(h)

Target Definition: Design Requirements

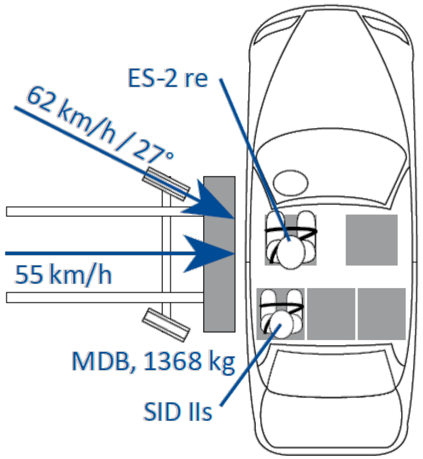
Dynamic load cases

1. FMVSS 214s (static)



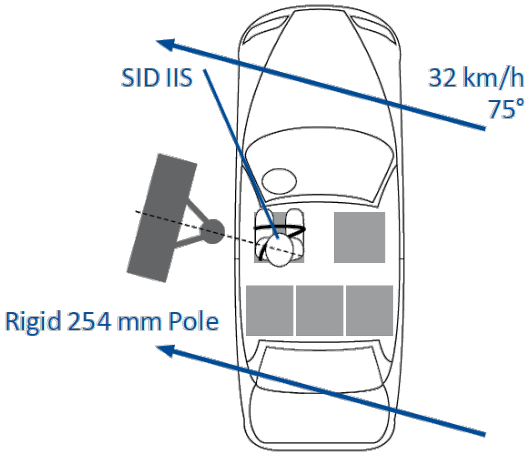
A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

2. FMVSS 214 (DB)



A moving deformable barrier is impacted with a stationary vehicle at 55 km/h.

1. FMVSS 214 (RP)



The vehicle is rammed into a rigid pole at 32 km/h at 75 deg.

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

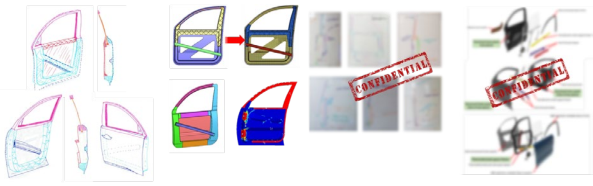
$$\begin{Bmatrix} f_1 \\ V_1 \\ M_1 \\ f_2 \\ V_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 & 0 & -\frac{AE}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{AE}{L}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

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

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

Phase 2

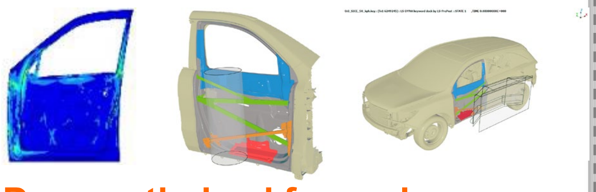
Concept Development



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

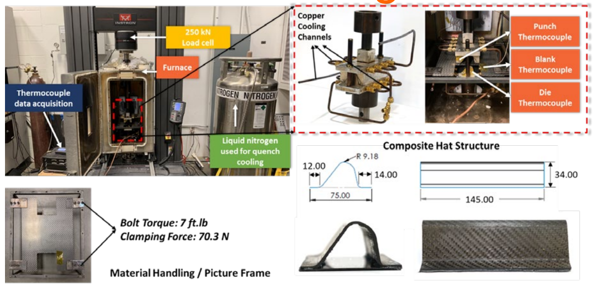
Phase 3

Subcomponent Testing

Calibrating and Validating MAT 54 Cards in Dynamic environment

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

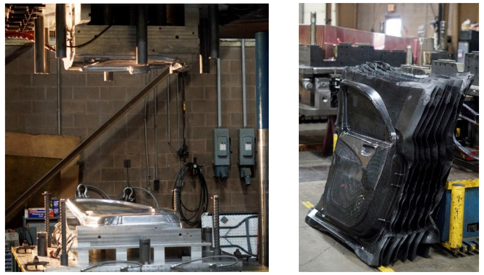
Thermoforming Trials



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

Phase 4

Tooling + Prototyping



Leveraging experience of suppliers like Proper Tooling + Lanxess

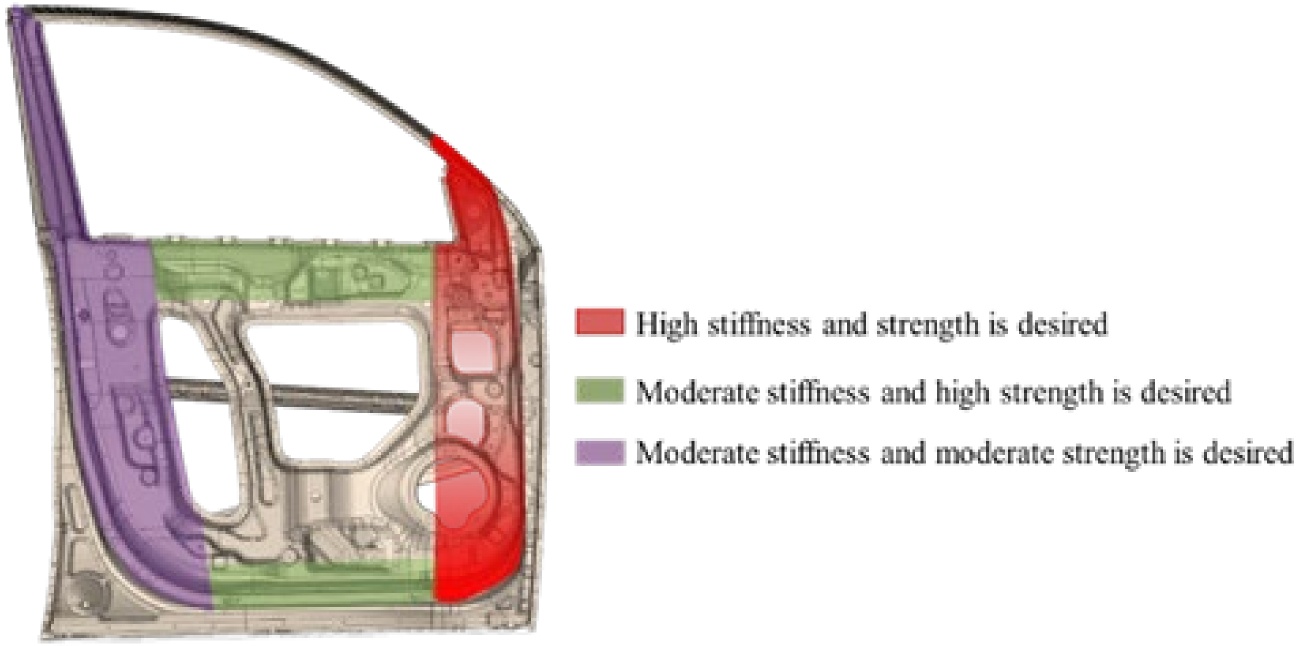
Glass & Carbon Doors Manufactured & Assembled
Quasi static & Dynamic tests performed

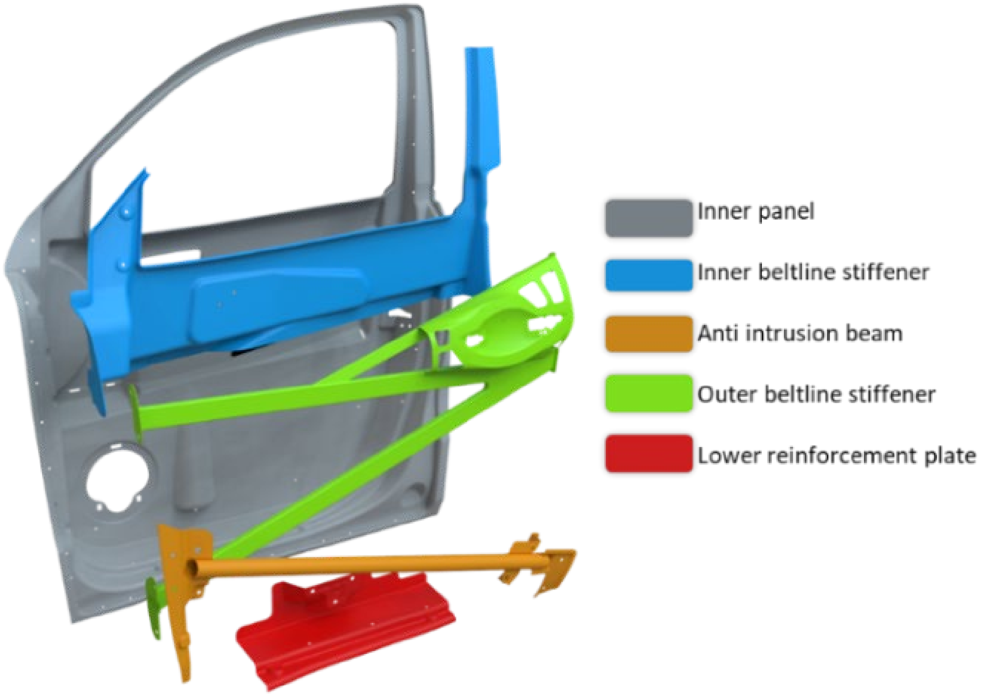
Testing

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

Design Study

- Static tests are first carried out on OEM's baseline steel door model for benchmarking.
- Initial investigations carried out on *Carbon/PA6 composite system* and optimized design is obtained.
- Material model used based on experimental characterization.





Design Optimization

Optimization problem

Objective function: $$\min.\left(\sum_{i=1}^{n} W_i\right) \qquad i = 1, 2, \ldots, n$$

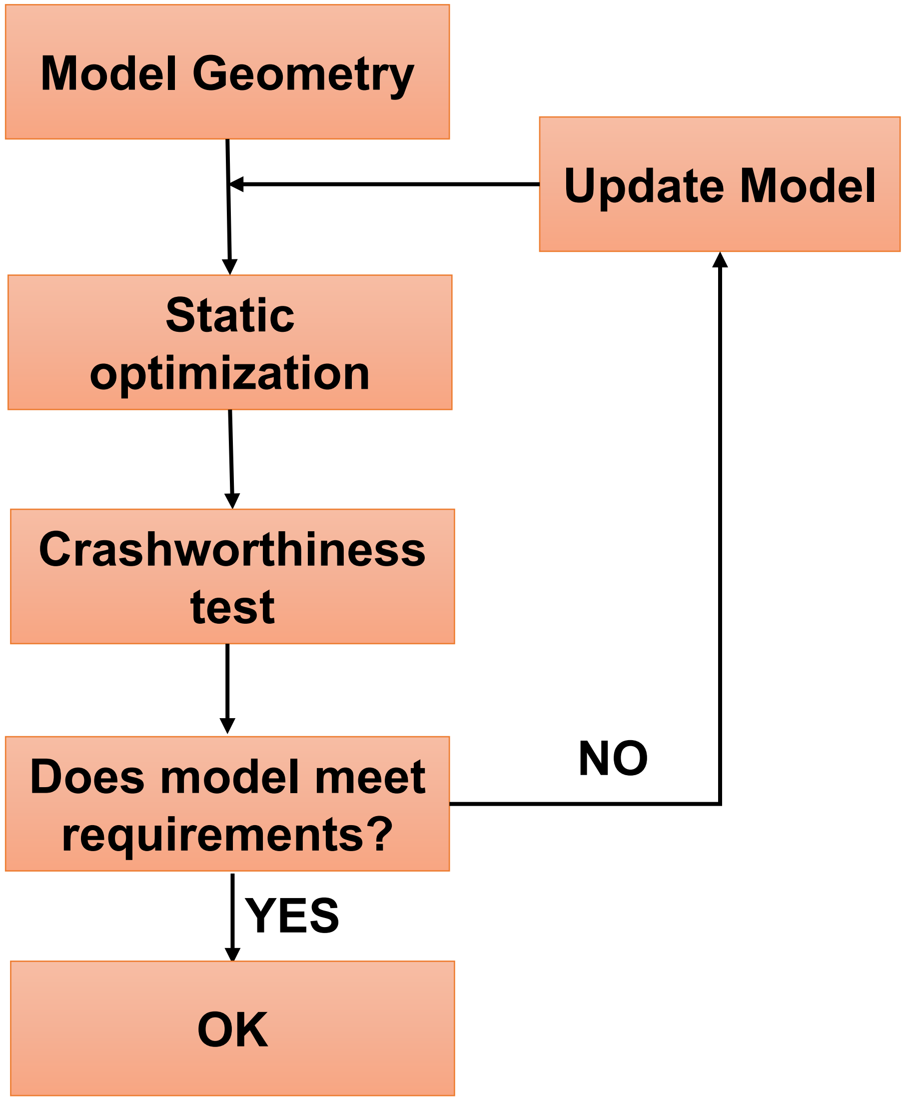
Constraints:

$$u_j < u_j^{req} \qquad j = 1, 2, \ldots, m$$

$$t_{mfr} < t_i < t_{initial} \qquad i = 1, 2, \ldots, n$$

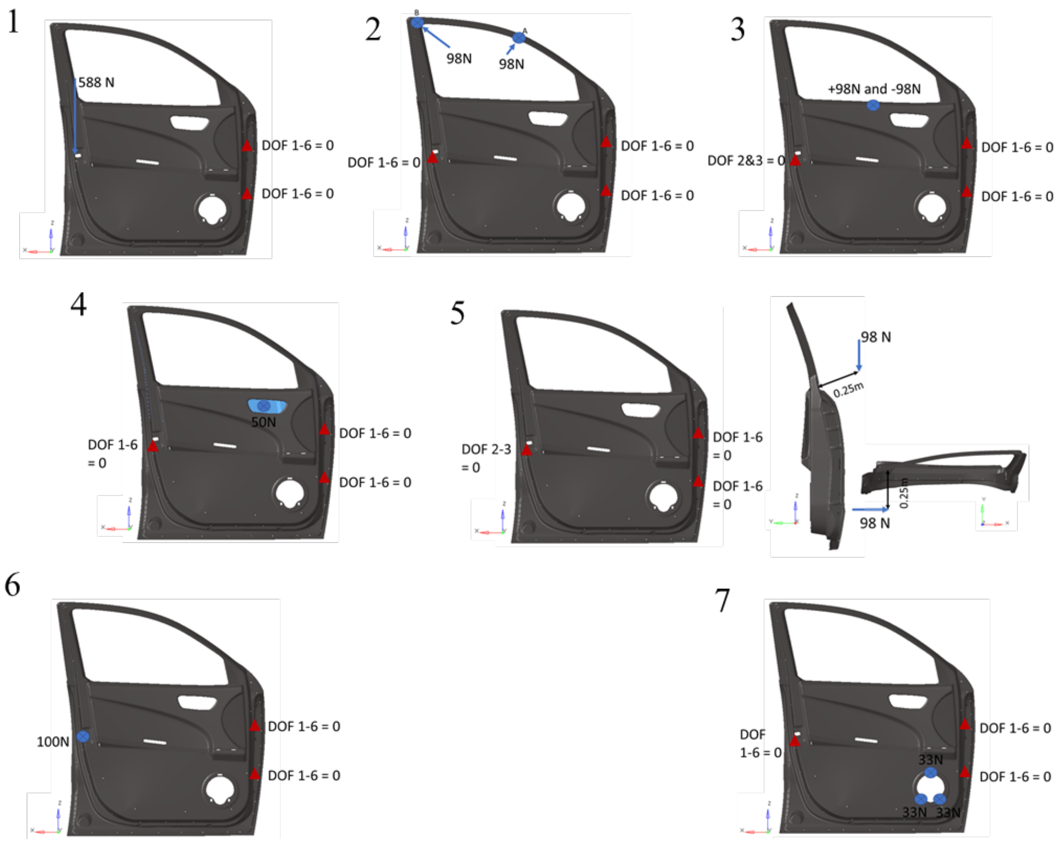
$$t_{ply} = k \cdot t_{ply}^{\min} \qquad k \text{ is an integer} \geq 0$$

n **– Total number of door subcomponents;**
k **– Total number of static load cases;**
W_i **–Weight of** i_{th} **subcomponent;**
u_j **– Displacement response for** j_{th} **load case;**
u_j^{req} **– Required displacement response for** j_{th} **load case;**
t_{mfr} **– Minimum manufacturable thickness;**
t_i **– Total thickness of subcomponent** ***i*****;**
$t_{initial}$ **– Initial input thickness.**
t_{ply}^{min} **= 0.15 mm is minimum ply thickness constraint**



Static Performance

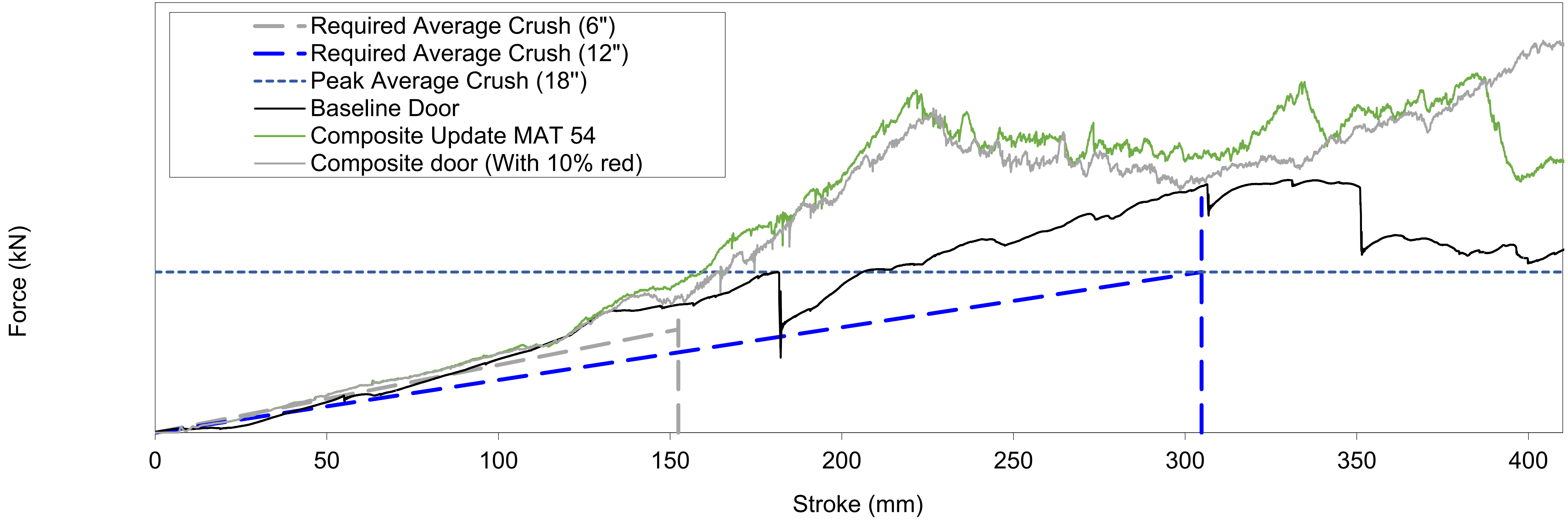
- The composite design optimization is carried out for the listed static load cases.
- All static load cases are well satisfied for the composite door.



S No.	Target category Subcase		Target values (units)			Composite door
A	Mass Target					
1		Structural frame mass	<	7.42	Kg	45%
2		Total mass	<	18	Kg	32%
B	Frame Related					
1		Door Sag - Fully open	<	5	mm	32%
2a		Sash Rigidity at point A	<	3.5	mm	10%
2b		Sash Rigidity at point B	<	4	mm	55%
3		Beltline stiffness-Inner panel	<	1.5	mm	79%
4		Window regulator (Normal)	<	1	mm	69%
5a		Mirror Mount rigidity in X	<	0.92	mm	1%
5b		Mirror Mount rigidity in Y	<	2.25	mm	67%
6		Door Over opening	<	24.7	mm	1%
7		Speaker mount stiffness	<	0.35	mm	48%
8		Outer panel stiffness	<	7.8	mm	80%

Quasi-static pole test (FMVSS 214S)

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



Results	Updated MAT CARD	10 % Reduced Properties
Initial Average Crush	23%	20%
Intermediate Average Crush	104%	93%
Peak Crush	124%	102%

Dynamic Performance

- 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%)

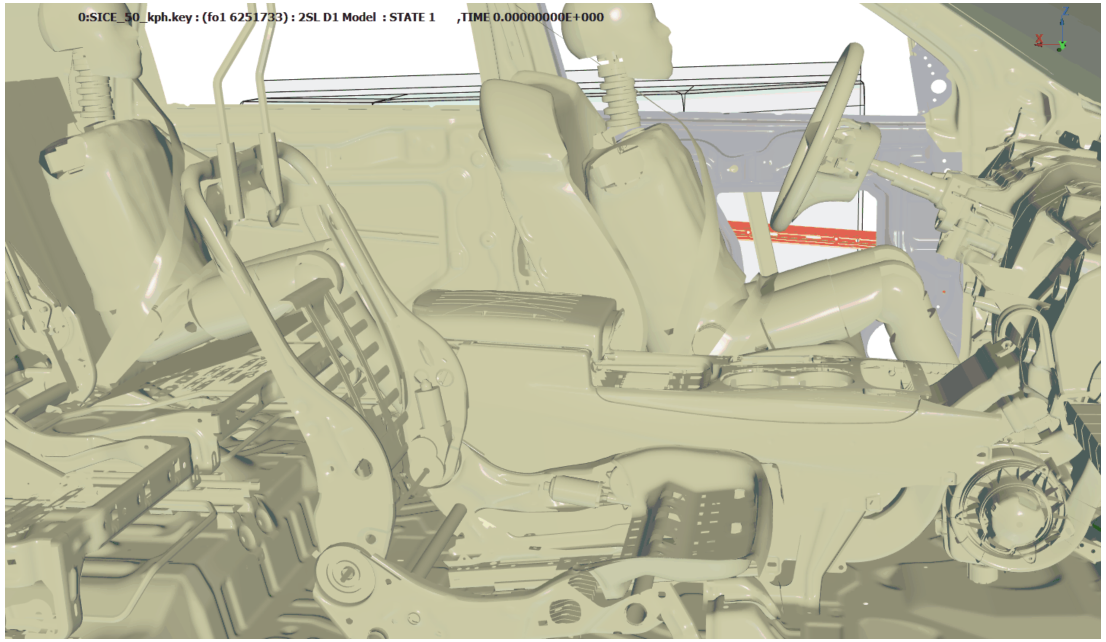
Key Performance Indicator	Composite [mm]	Composite 10% reduced [mm]
Safety survival space	(4%)	(4%)
Max roof intrusion	(4%)	(6%)
Max windowsill intrusion	(14%)	(15%)
Front door dummy hip intrusion	(22%)	(23%)
Max door lower intrusion	(1.5%)	(1.2%)

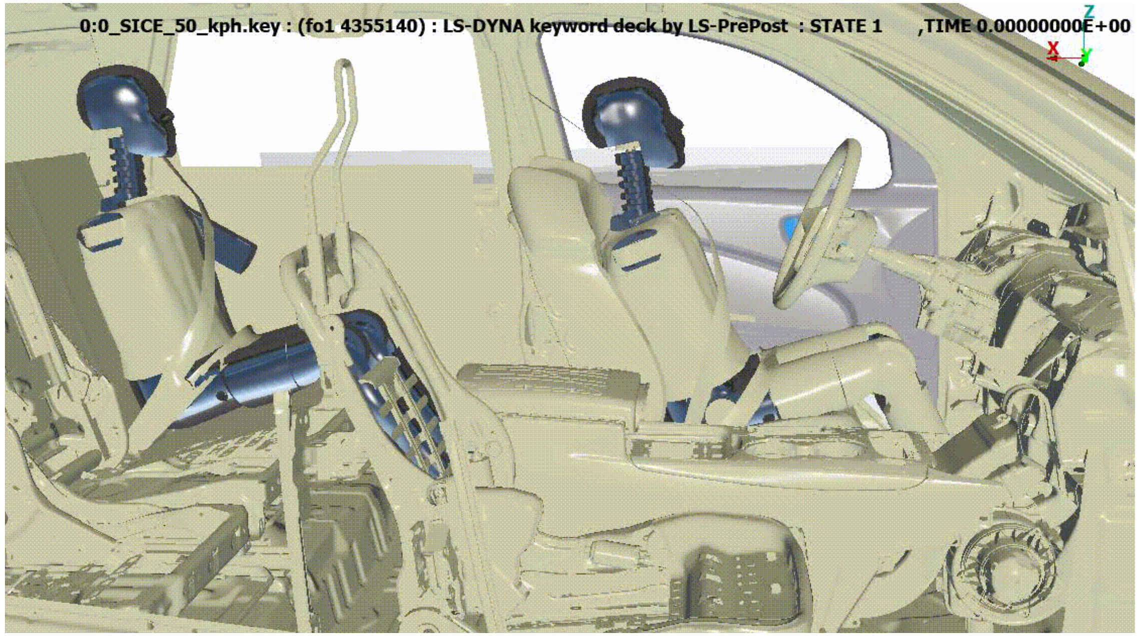
Dynamic Performance

IIHS Side Impact – moving deformable barrier

- No exposed crack in the door interior

MAT 54 Card developed and calibrated at Clemson Composites Center as part of the manufacturing to response pathway



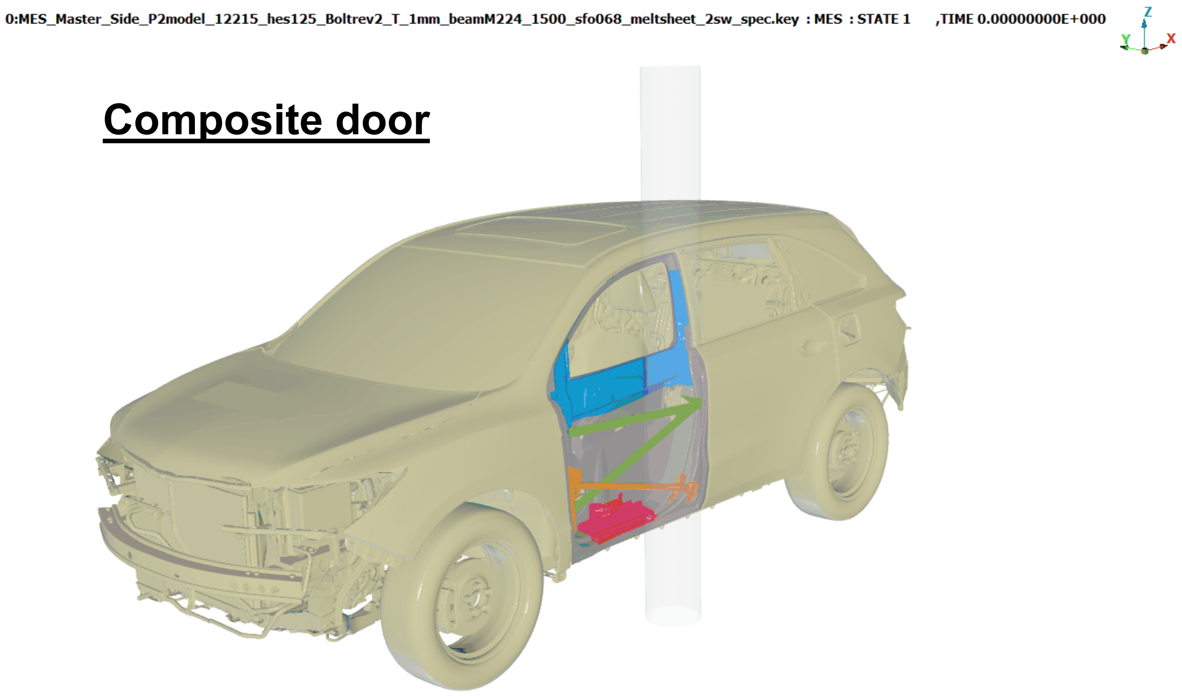


FMVSS 214 Rigid Pole

- The vehicle is mounted on a mobile platform and is impacted with a rigid pole at 75° to its length
- For this test, a hybrid III 5th percentile female crash dummy was used for positioning the vehicle since it is the most challenging crash mode for the rigid pole test
- The composite door had adequate performance in this test

Baseline steel door

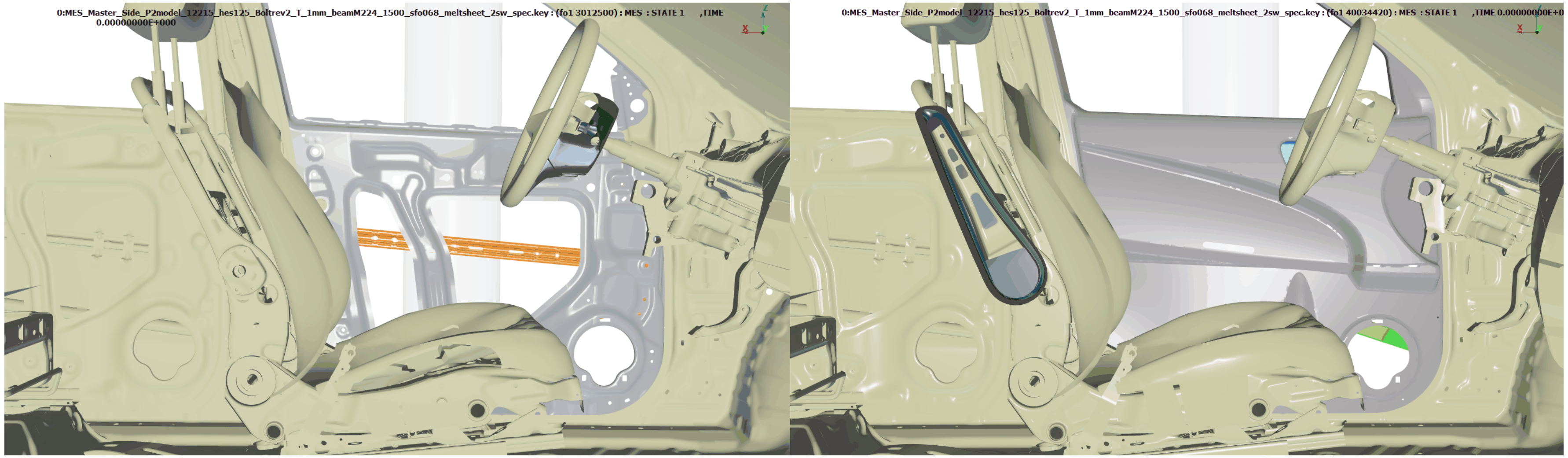
Composite door



Dynamic Performance

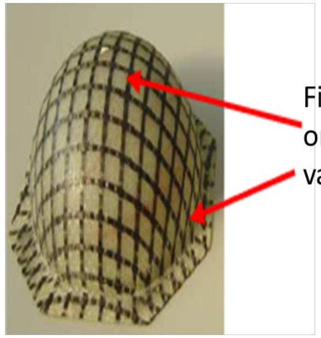
- **Success** **(Green)**
  - Below baseline target values (<b)
- **Tolerable** **(Yellow)**
  - More than baseline values but smaller than 10 % difference (>b, <b+10%)
- **Failure** **(Red)**
  - More than 10% above baseline value (>b+10%)
- **No exposed crack in the door interior.**

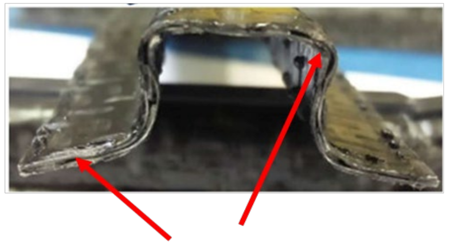
Key Performance Indicator	Difference [mm]	Difference [%]
Maximum intrusion at B-pillar	13.1	8.68%
Maximum intrusion at sill intrusion	-5.8	-1.98%
Maximum intrusion at roof	5.8	2.28%
Maximum intrusion at window sill intrusion	3.6	0.83%
Intrusion at Hip location of the dummy	-18.8	-5.29%
Maximum intrusion at lower door region	2.8	0.64%

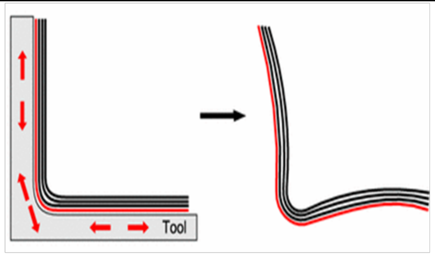


How good are these model predictions?

Manufacturing process induced effects







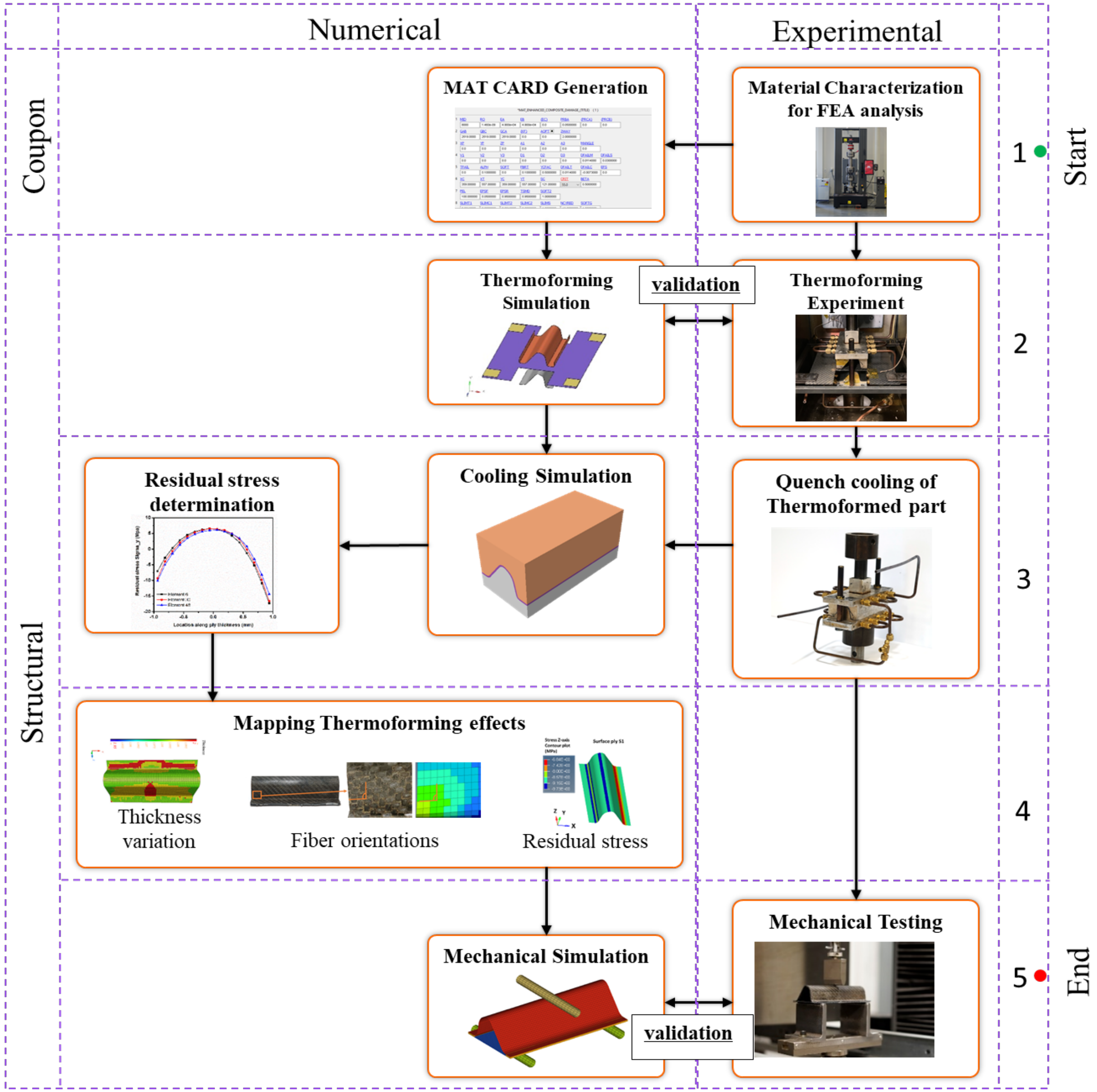
Residual stress induced warpage

Examples

- 45% overestimation of displacements was predicted from structural analysis when fiber reorientation was neglected in a hemispherical dome structure [1]
- Considering effect of fiber reorientation and thickness variation on material properties, the reaction force response for as-designed and as-built structures showed difference of upto 18% [2]
- Increased cure temperature resulted in 25% increase in residual stresses causing 16% reduction in composites' short beam shear strength [3]

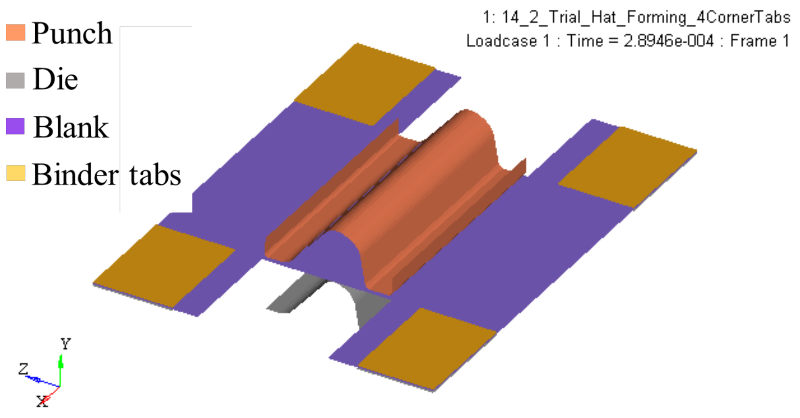
[1] Nino GF, Bergsma OK, Bersee HE, Beukers A. Influence of fiber orientation on mechanical performance for thermoformed composites. ICCM Int Conf Compos Mater 2007:1–7.
[2] Mayer N, Prowe J, Havar T, Hinterhölzl R, Drechsler K. Structural analysis of composite components considering manufacturing effect. Compos Struct 2016;140:776–82. https://doi.org/10.1016/j.compstruct.2016.01.023.
[3] Agius SL, Joosten M, Trippit B, Wang CH, Hilditch T. Rapidly cured epoxy/anhydride composites: Effect of residual stress on laminate shear strength. Compos Part A Appl Sci Manuf 2016;90:125–36. https://doi.org/10.1016/j.compositesa.2016.06.013.

Manufacturing-to-Response Pathway

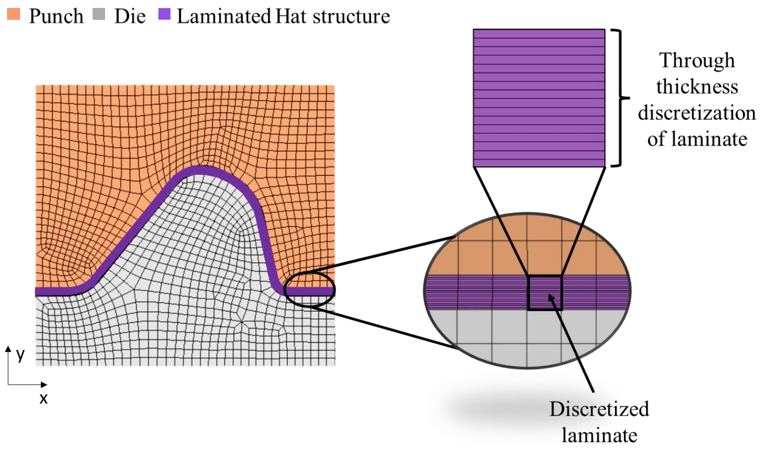


- MAT cards generated for simulations
- Cooling temperature curves from thermoforming trials used as input for cooling analysis
- Classical laminate theory implemented for residual stress determination
- Thermoforming process effects mapped for structural analysis
- Quasi-static: 3-point bending and Dynamic: drop tower test performance validated

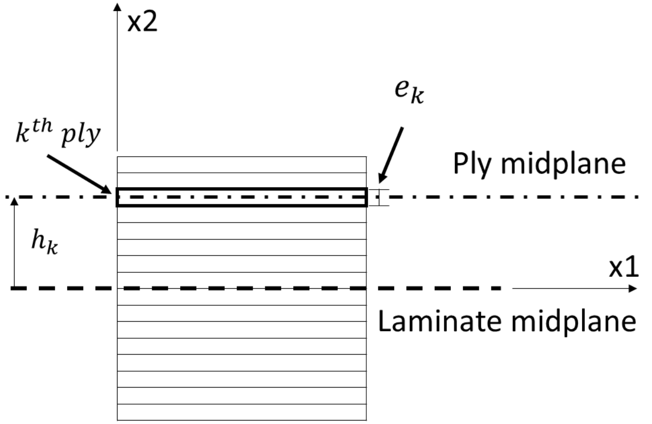
Modeling Pathway



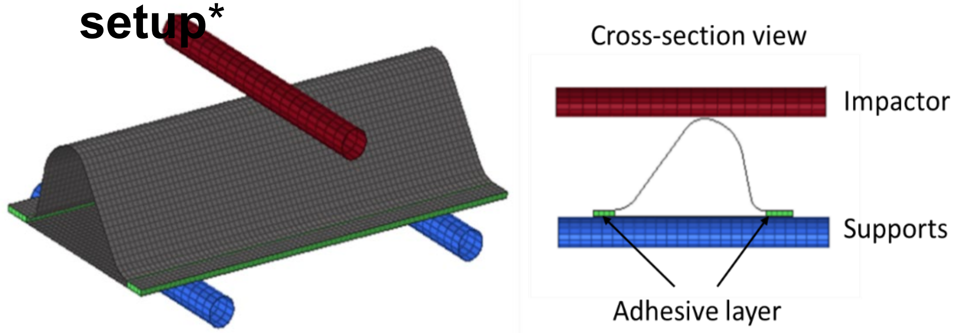
Cooling analysis



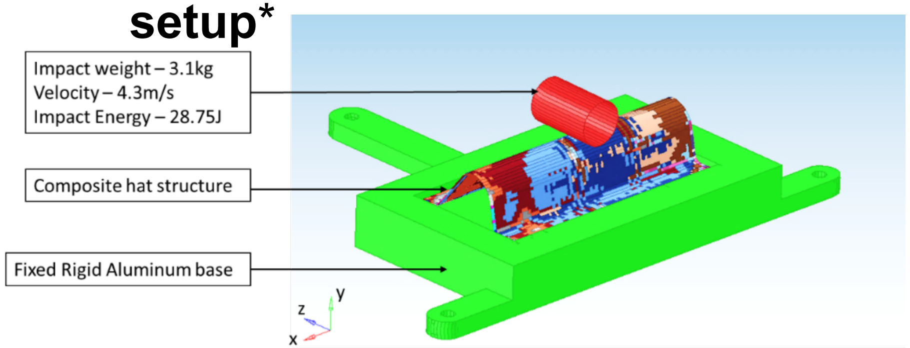
Residual stress calculation



Quasi-static: 3-point bending setup*



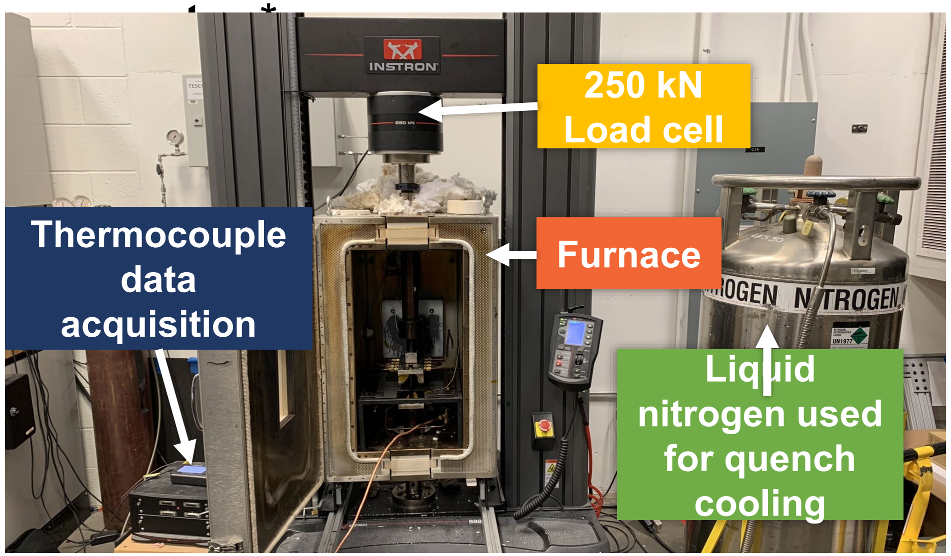
Dynamic: Drop tower test setup*

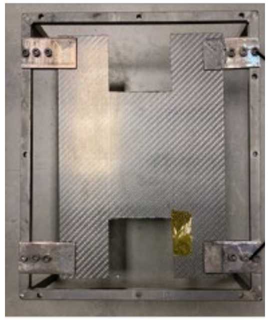


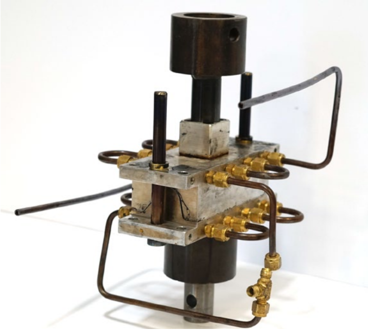
- Fiber orientations and thickness results from forming and thermally induced residual stresses are mapped to perform quasi-static and dynamic analysis

Experimental Pathway

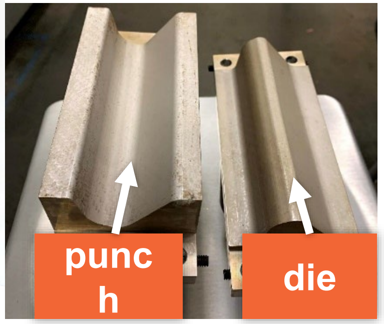
Thermoforming experimental





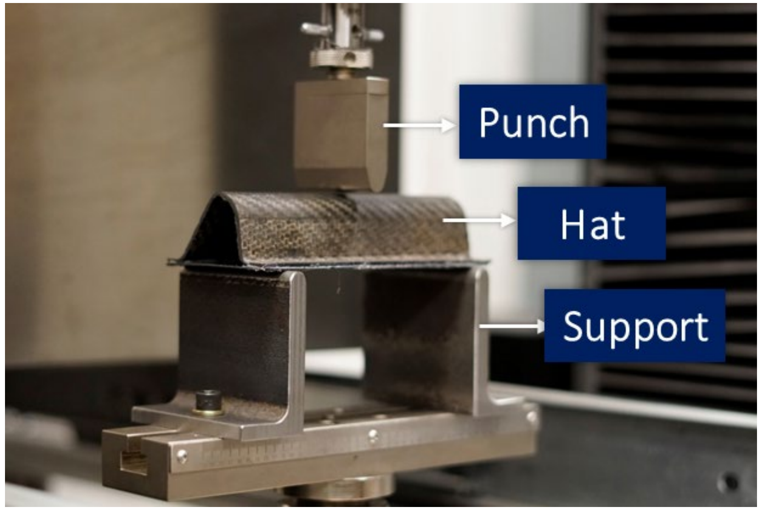


Copper cooling channels

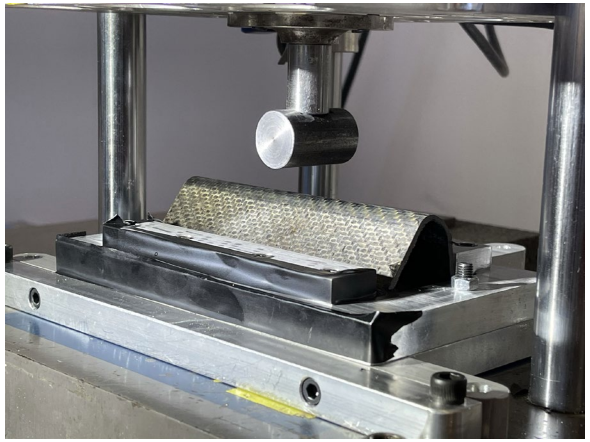


Tool-set

Quasi-static: 3-point bending setup*



Dynamic: Drop tower test setup*



- 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**

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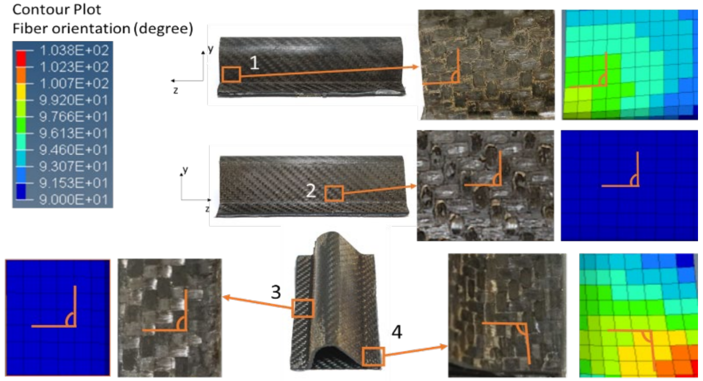
Model Validation

Thickness variation

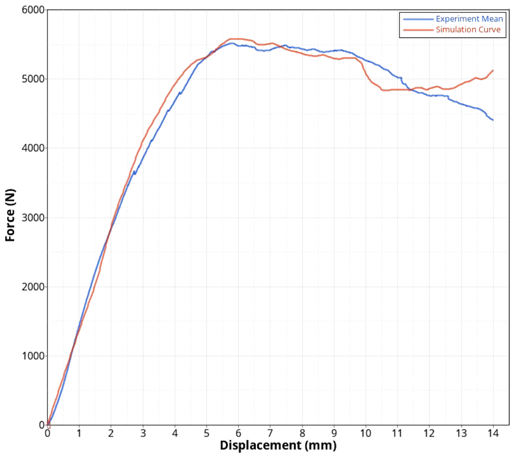
Max: 2.01mm, Min: 1.97mm

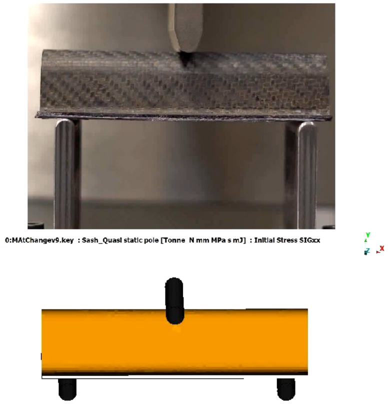
Fiber reorientations



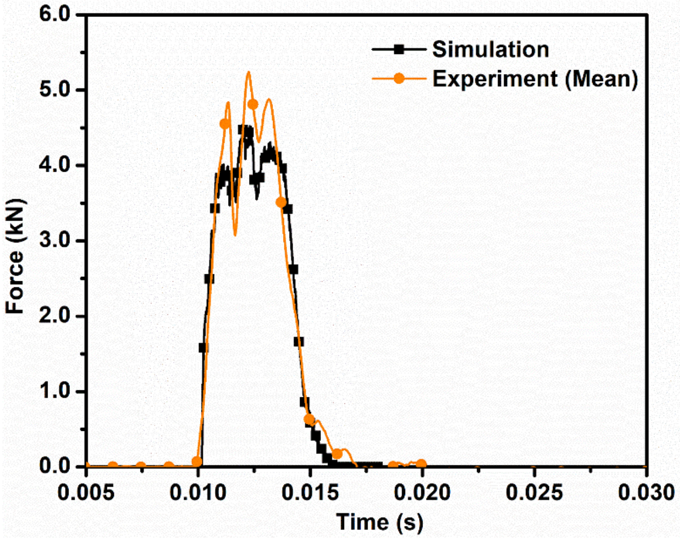
Max: 13 °, Min: 0°

Quasi-static: 3-point bending test*





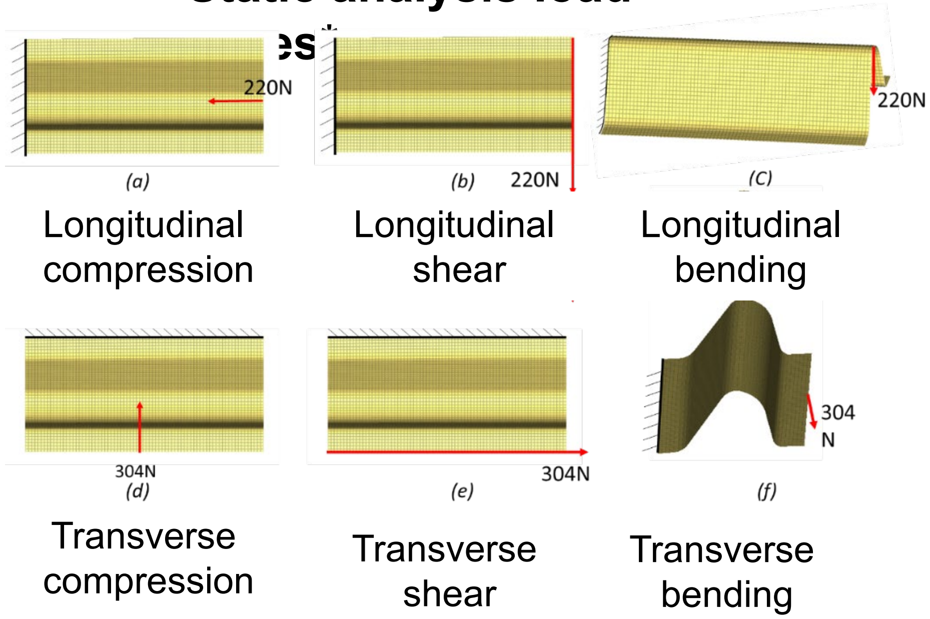
Dynamic: Drop tower test*



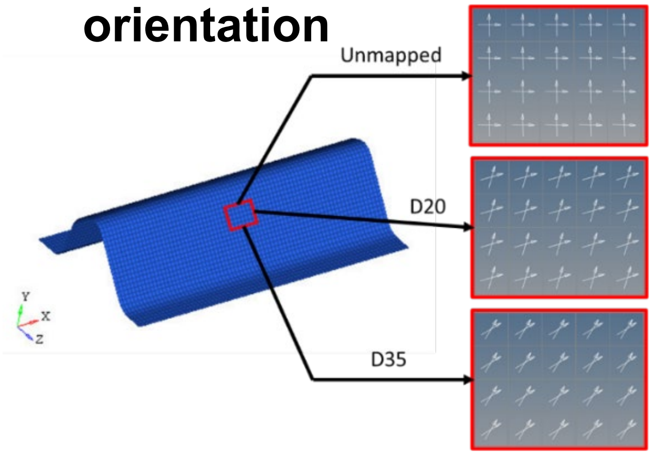
- **A comparison between the measured thickness and predicted thickness shows a good agreement**
- **The force-displacement responses from bending test show a very good agreement till damage onset**
- **Maximum impactor stroke of 7.35 mm obtained from the dynamic simulation is very close to the mean experiment maximum stroke**

Effects on Static Performance

Static analysis load



Change in fiber orientation

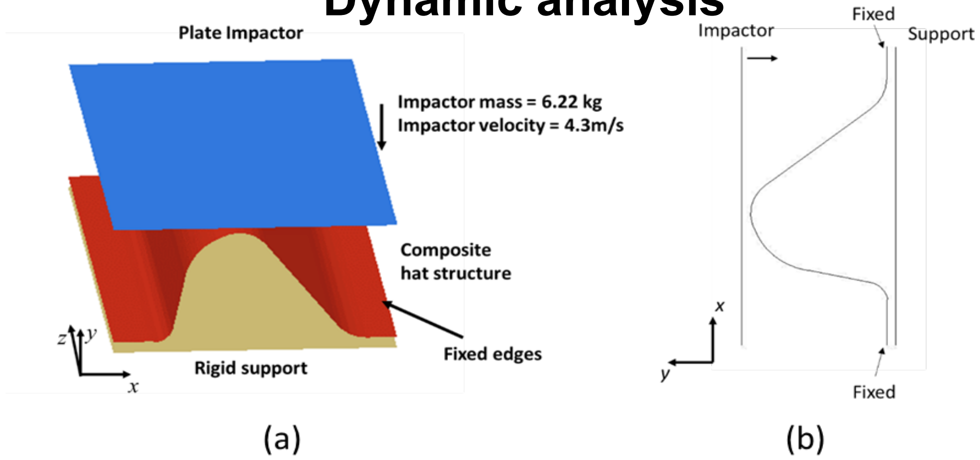


- Static test is carried out to evaluate the deflection of the hat structure by applying force of 4 N to each node of the loading edge.

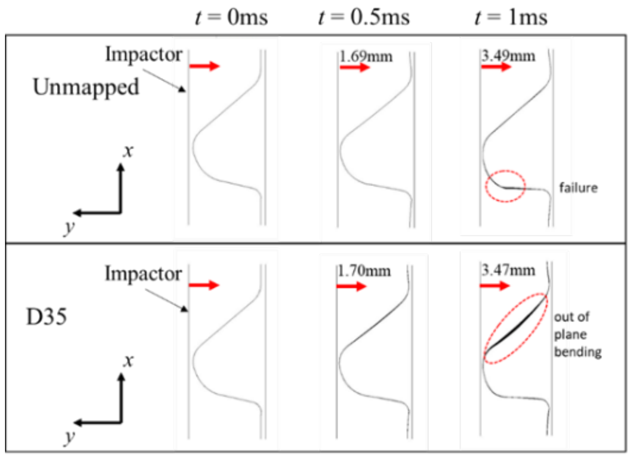
- **Effects of thickness:**
  - Higher thickness variation increased deflection for all load cases with a maximum increase of 16% for transverse bending case.
- **Effects of fiber orientation:**
  - Higher fiber reorientation severely reduced stiffness for compression cases
- **Effects of cooling rate:**
  - Higher cooling rate significantly reduced longitudinal compression stiffness shown by increase in deflection by 13% from the unmapped case

Effects on Dynamic Performance

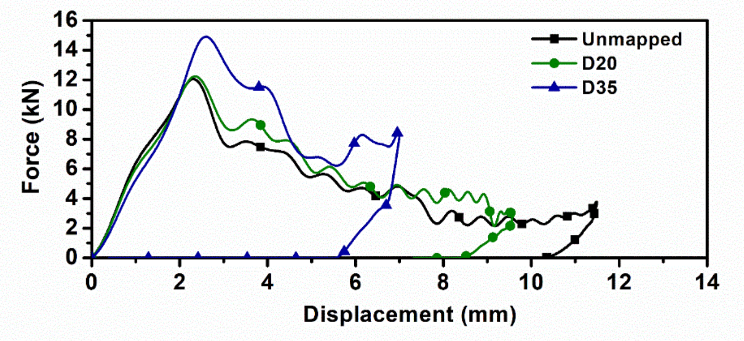
Dynamic analysis*



Progressive damage behavior for fiber orientation cases



Impact performance plots for fiber orientation cases



- Dynamic analysis is carried out to evaluate the impact performance of the hat structure by applying impact energy of 57.5 J
- **Effects of thickness:**
  - Higher thickness variation (the average thickness is reduced) reduced the initial crush stiffness and peak force
- **Effects of fiber orientation**
  - Higher fiber reorientation led to higher peak force caused by out of plane bending of larger edge of hat structure
- **Effects of cooling rate:**
  - The hat structure is pre-stressed with compressive residual stresses
  - Higher cooling rate reduced compressive stiffness and hence lowered peak force

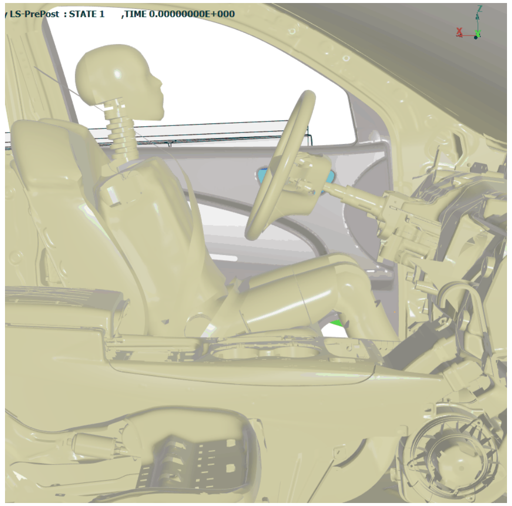
Incorporating Manufacturing Effects in Design

1. Integrated manufacturing and design optimization
2. Manufacturing-effect-aware design optimization
3. Design optimization to minimize manufacturing effect

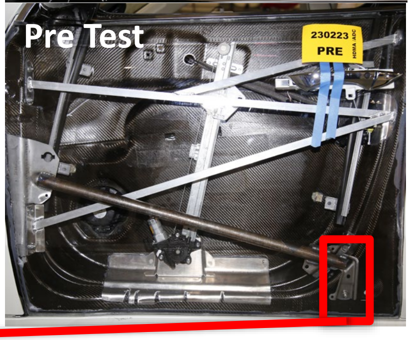
Movable deformable barrier

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 gauging metric 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%)



Key Performance Indicator	Composite Response Simulation [mm]	Composite Response Tested [mm]
Safety survival space (Hip Intrusion)	4%	6.8%
Max roof intrusion	4%	NA
Max windowsill intrusion	14%	14 %
Front door dummy hip intrusion	22%	23%
Max door lower intrusion	1.5%	+23%



The carryover steel bracket from the baseline steel door failed catastrophically into two pieces, with the adhesively joint piece still bonded to composite inner panel. To prevent this from happening again, the OEM will increase the bracket's thickness.

Intrusion over several critical performance indicators on the composite door were significantly higher than the OEM requirements.

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- Dr. Paul Venhovens (Faculty)
- Melur (Ram) K. Ramasubramanian (Faculty)

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- 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)

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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

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Conclusion

- An integrated approach of design, analysis and optimization for developing and designing the ultra-lightweight thermoplastic composite door
- All the static and dynamic load case requirements are satisfied
- An MTR pathway is established to link the manufacturing process effects to the mechanical responses.
- The process effects show considerable impact on performance underscoring the need for such a pathway to develop high performance structures.