Design Development of an ultra-lightweight carbon fiber reinforced thermoplastics automotive closure system

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Grand Challenge

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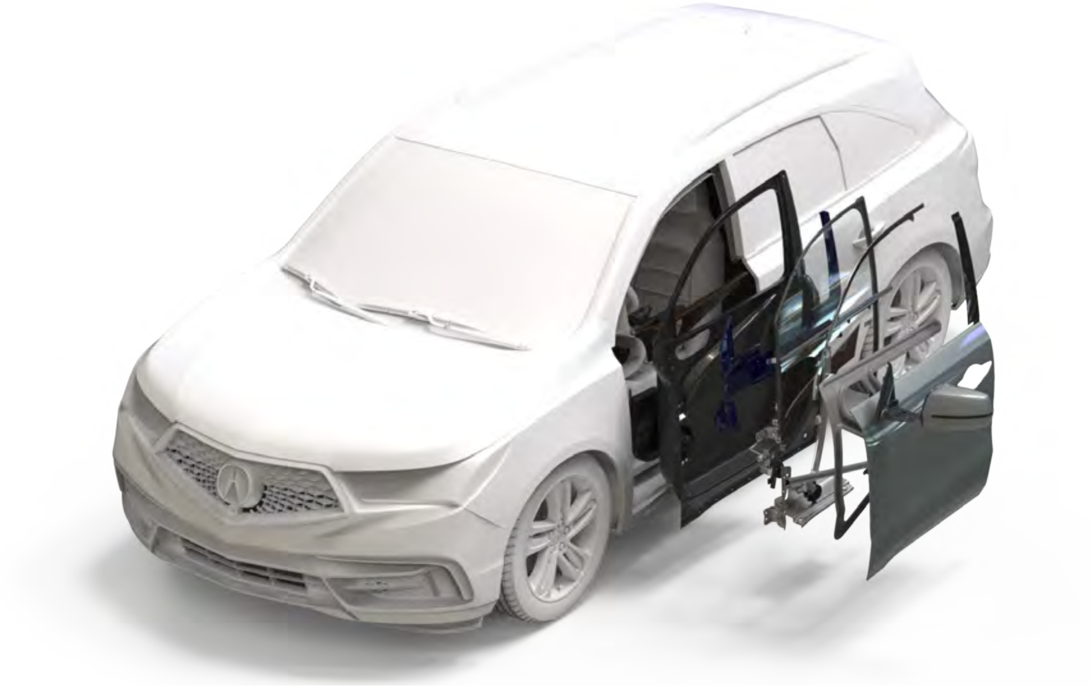
1. **Achieve a 42.5% weight reduction (addresses goals in the DOE-VT MYPP)**
   - Base weight = **31.8 kg**
   - Target Weight = **18.28 kg**

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. (.453 kg)**
   - 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)



Project Restriction

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› Constraint set fort by DOE
  - Has to be 100% recyclable
  - Need to use commercial available material systems
  - The prototype door has to meet all attributes of the baseline door.
  - Technology for scalability has to ready available

› Constraint set fort by Honda
  - Should use same sealing geometry
  - Should have all the equipment as the baseline door
  - Should have un-noticeable difference in Class A finish
  - Should meet all durability and aging requirements from Honda

Fine Prints of the Grand Challenge

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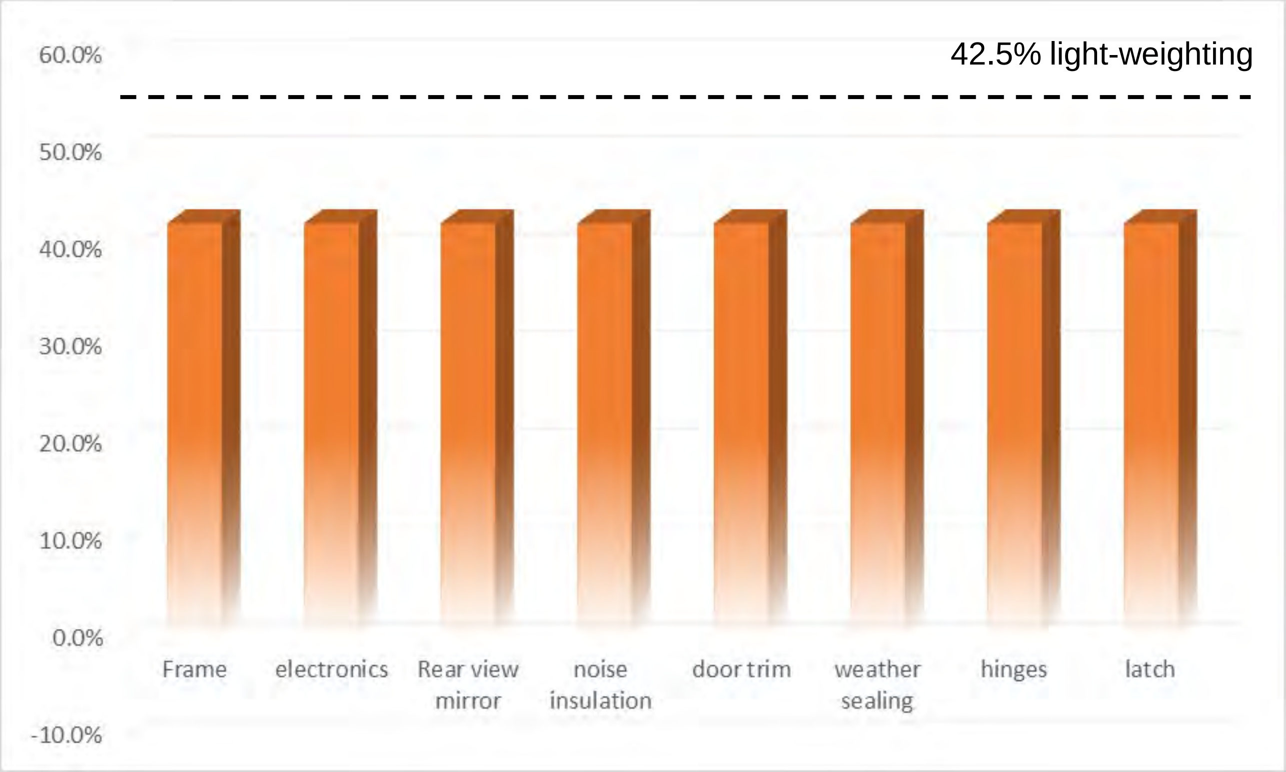
- Weight and cost target is for entire door assembly.
  - Not all components in the door assembly have equal lightweight potential
    - This drives a more aggressive target for the door frame.



"Material substitution is not a solution"

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Technical Challenges

- How do we go about exploring the design space with multiple combinations of materials, design geometries and manufacturing pathways?

- How do we ensure the right materials are used in the right locations in an efficient manner?

- How do we go about the development process as fidelity of information regarding the design and materials' behavior improves?

Target Definition: Big Picture

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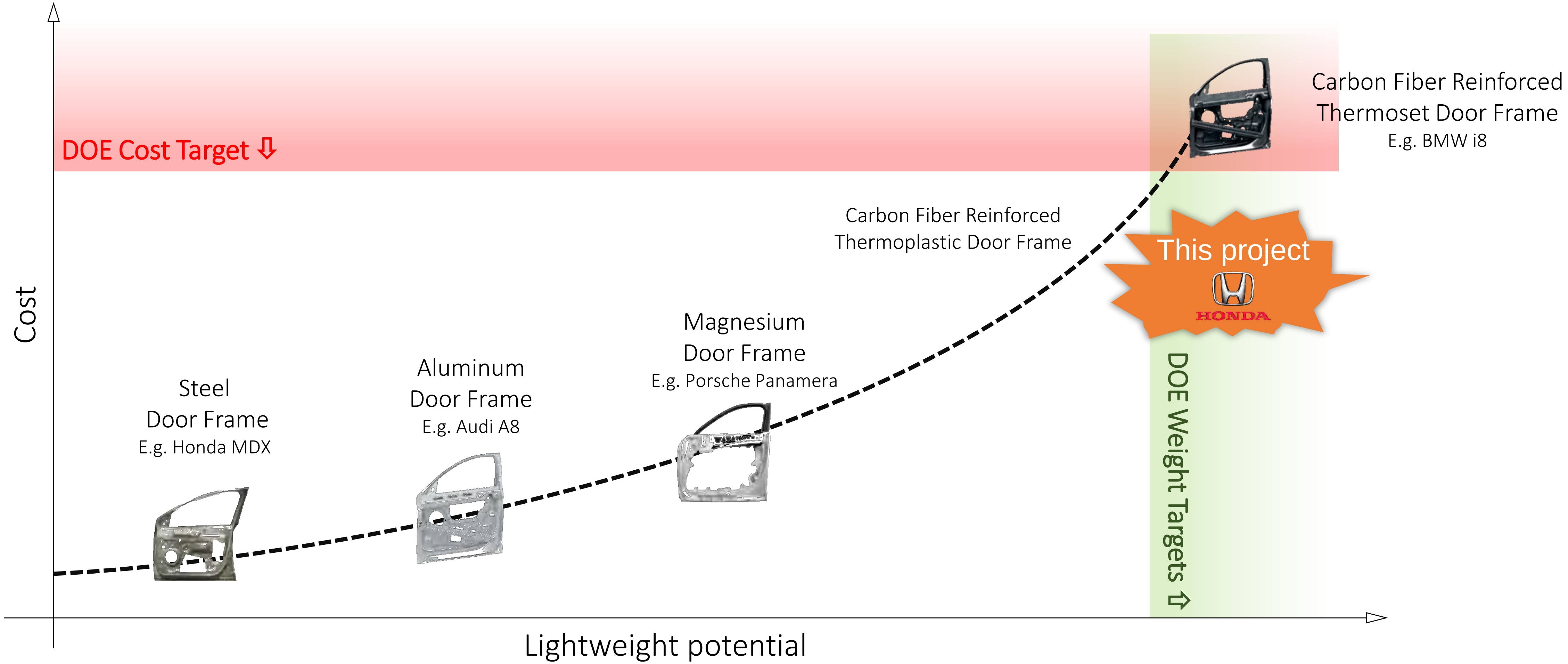
Benchmarking other lightweight door concepts and understanding performance vs cost tradeoffs.



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Why Systems Approach?

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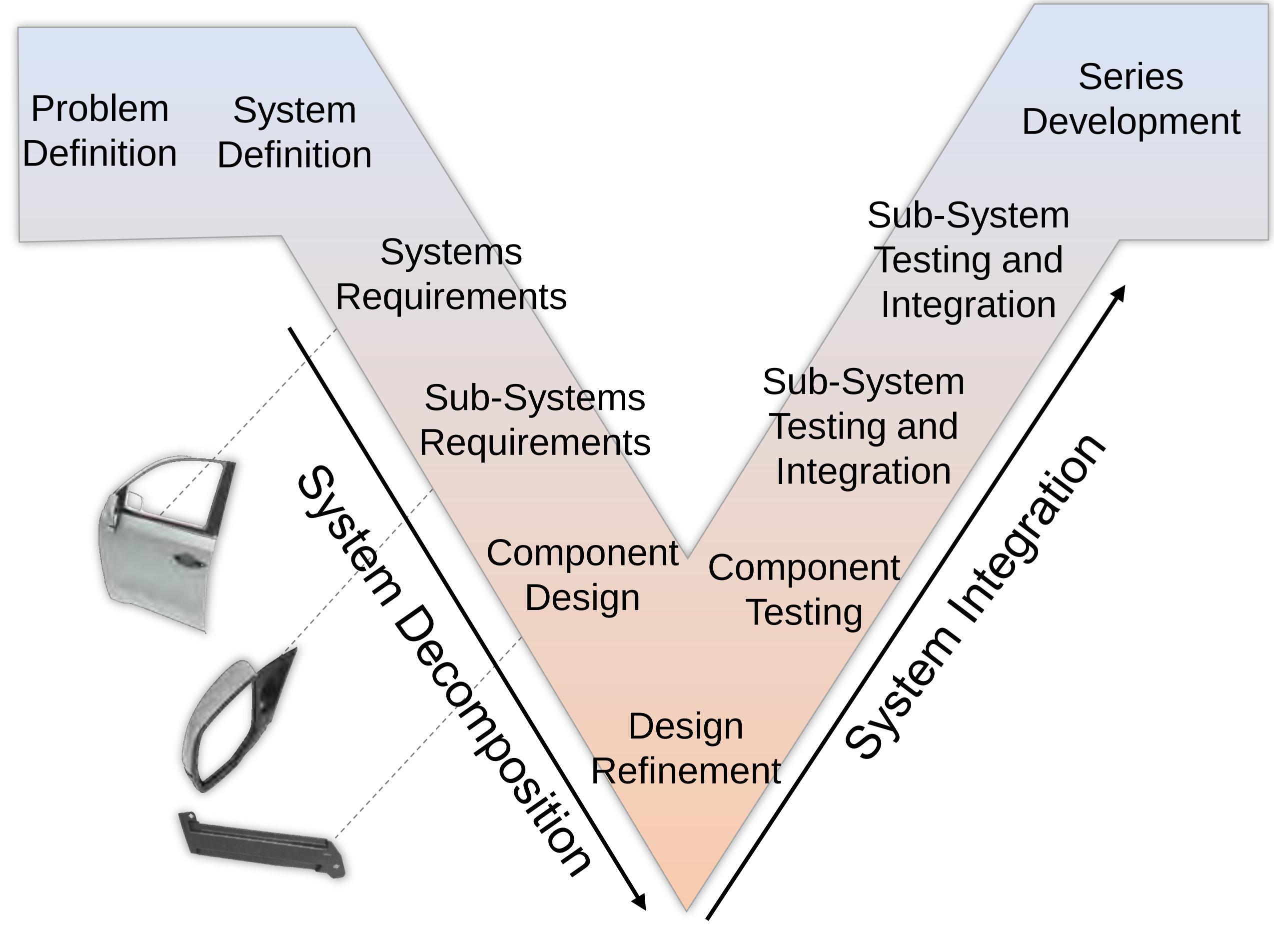
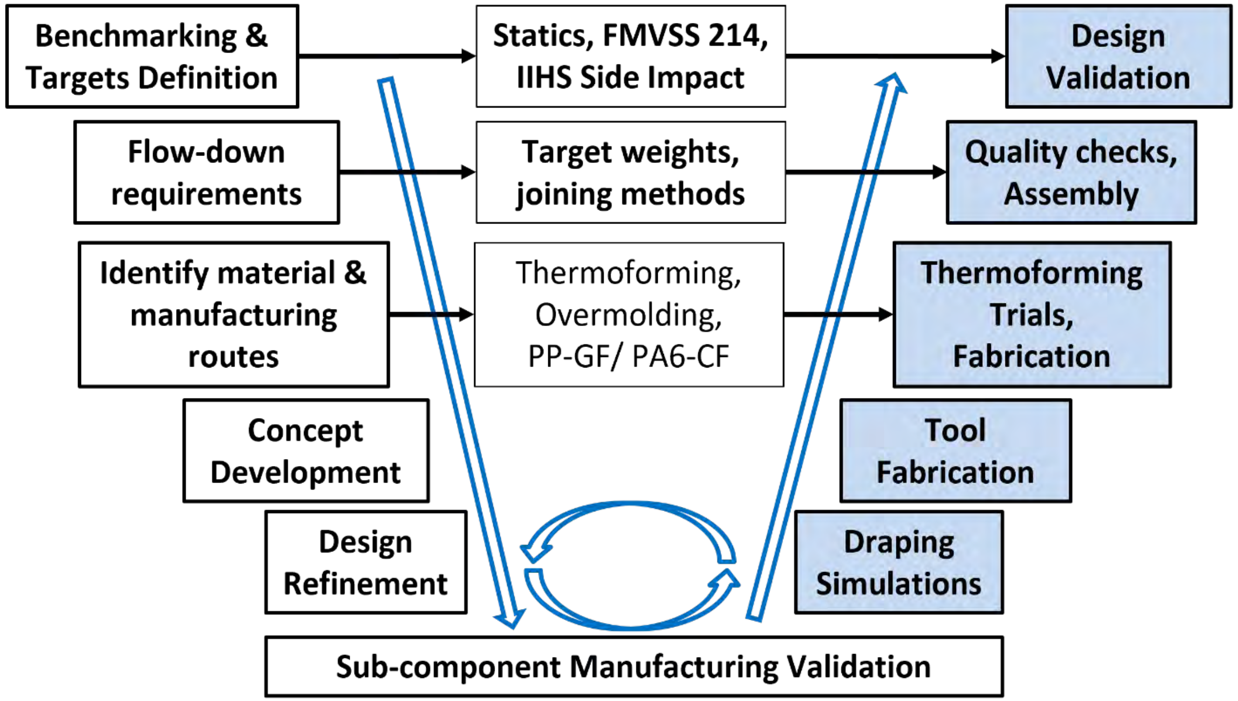
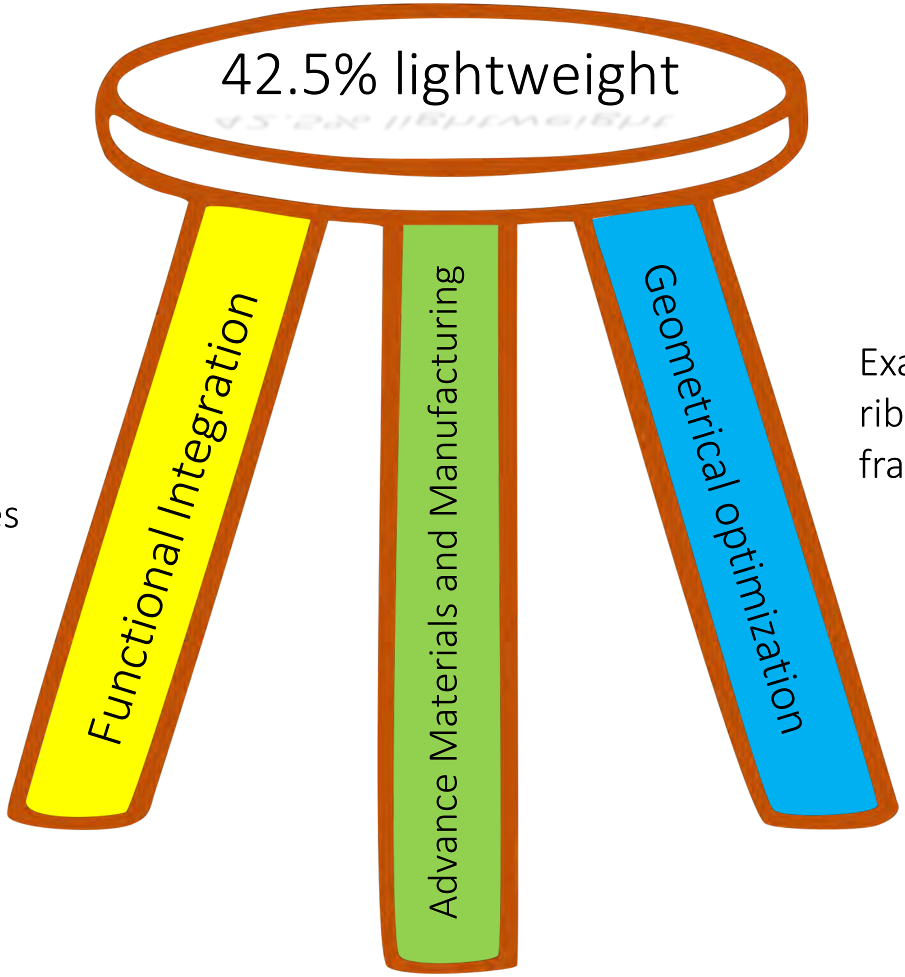
Understating requirement at system level and decomposing targets and definition to lower systems.





Design Requirements Breakdown



Example : The foamed polymer inner panel has desired properties of a noise isolator.

Example : Topology optimization for ribbed structure in the plastic frame for better load path

Example : local foaming in non load critical areas for light-weighting. Usage of UD tapes for load-paths.

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Approach

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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

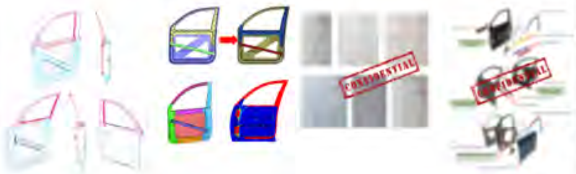
$$\begin{Bmatrix} f_1 \\ V_1 \\ M_1 \\ f_2 \\ V_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 & 0 & -\frac{AE}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{AE}{L}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

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

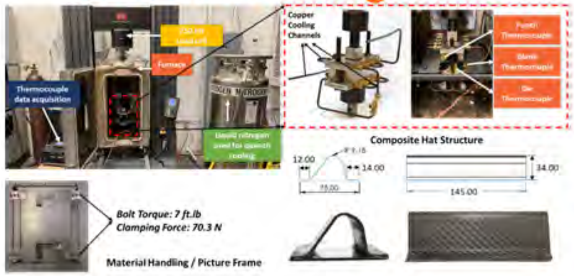
Phase 3

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

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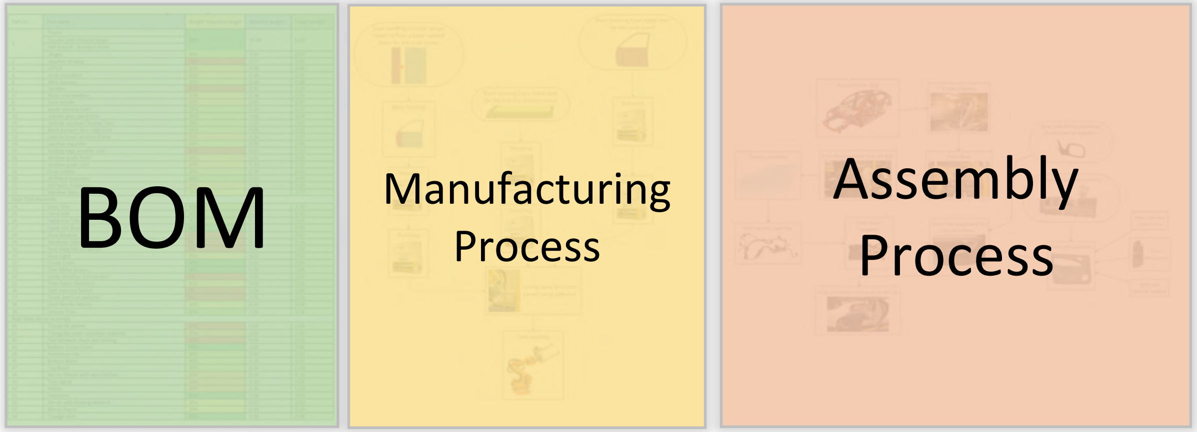
Baseline benchmarking

Teardown benchmarking

- Bill of materials with detailed weights
- Detailed manufacturing process
- Detailed assembly process



Baseline benchmarking

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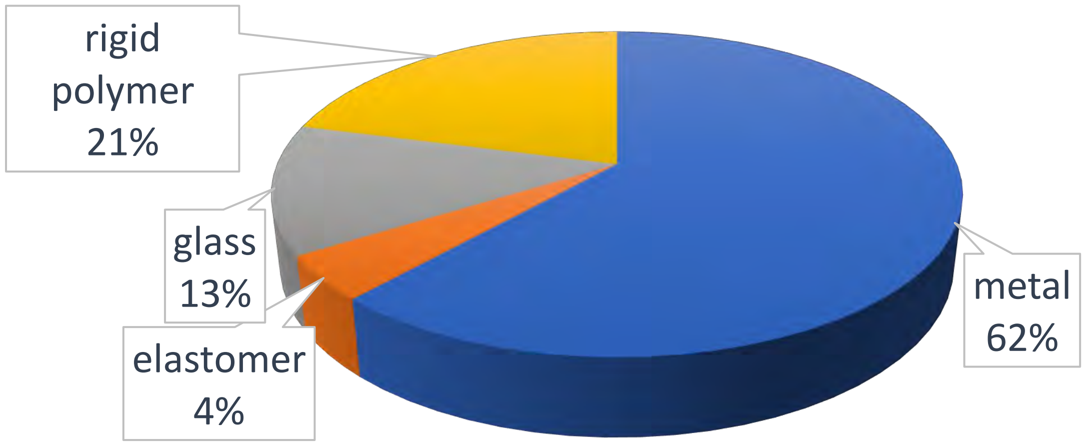

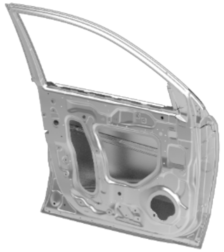

Frame 60% Reduction
Current weight : 15.45 kg
Target weight : 6.18 kg

Window 20% Reduction
Current weight : 3.70 kg
Target weight : 2.77 kg

Electronic 0% Reduction
Current weight : 3.0 kg
Target weight : 3.0 kg

Trim 30% Reduction
Or elimination
Current weight : 3.24 kg
Target weight : 2.26kg

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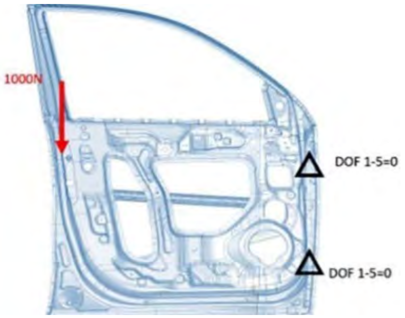
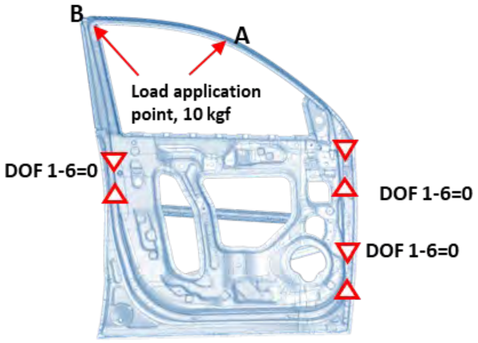
Phase I FEA Optimization : Static Load Cases

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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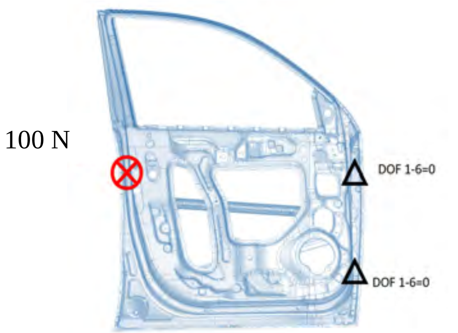

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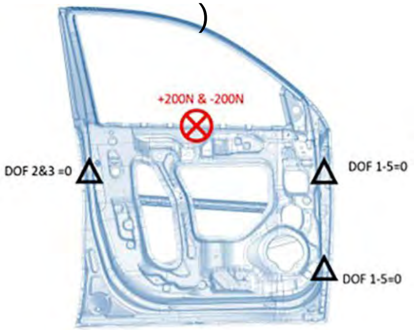

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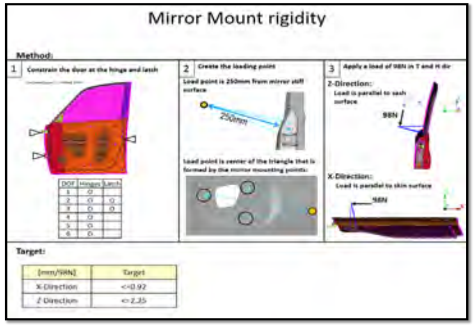

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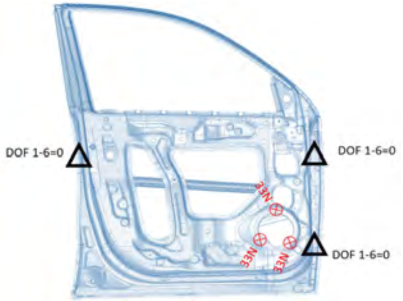

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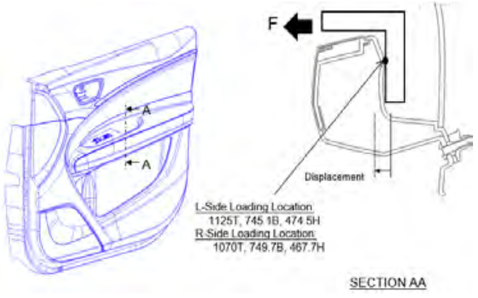

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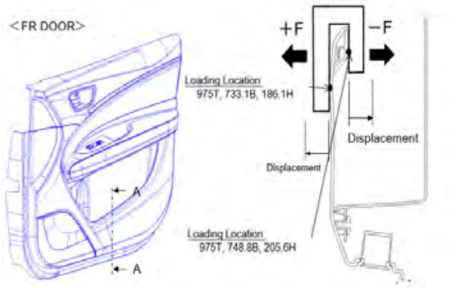

(h)

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Crash Performance: Dynamic Load Cases

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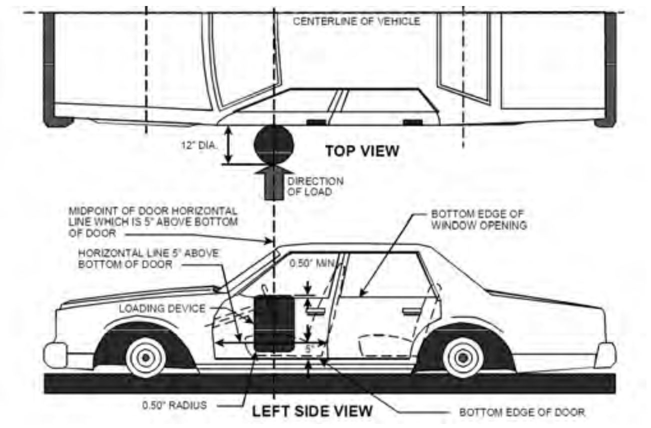
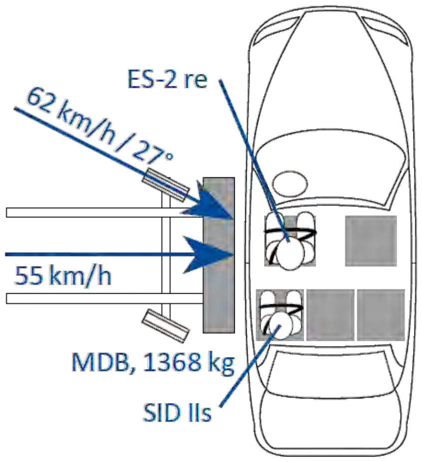
Dynamic load cases

1. FMVSS 214s (static)



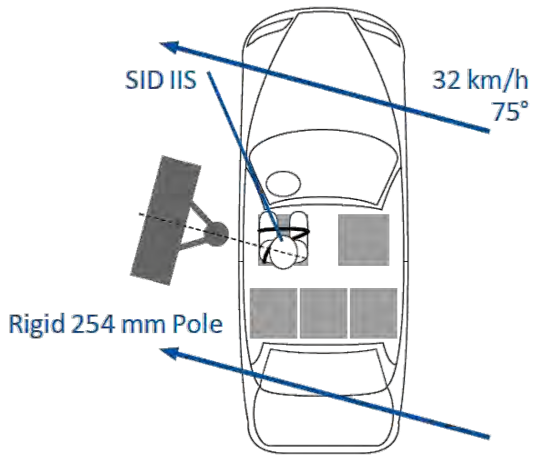
A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

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.

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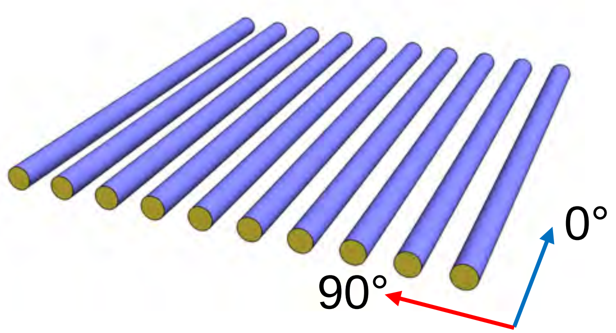
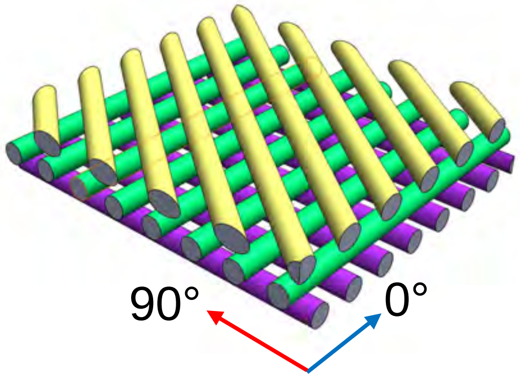
Modeling Endless Fiber & Woven Materials

- These are materials are anisotropic by design
- FEA Material model inputs known based on our MAT 54 card
- Good knowledge base for FEA simulation exists with our collaborators at Clemson University and University of Delaware

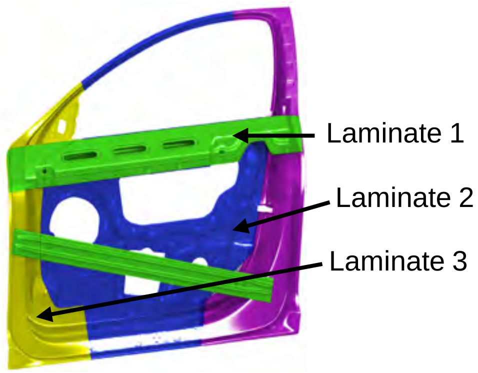
PLY



Laminate Design



Layup Design



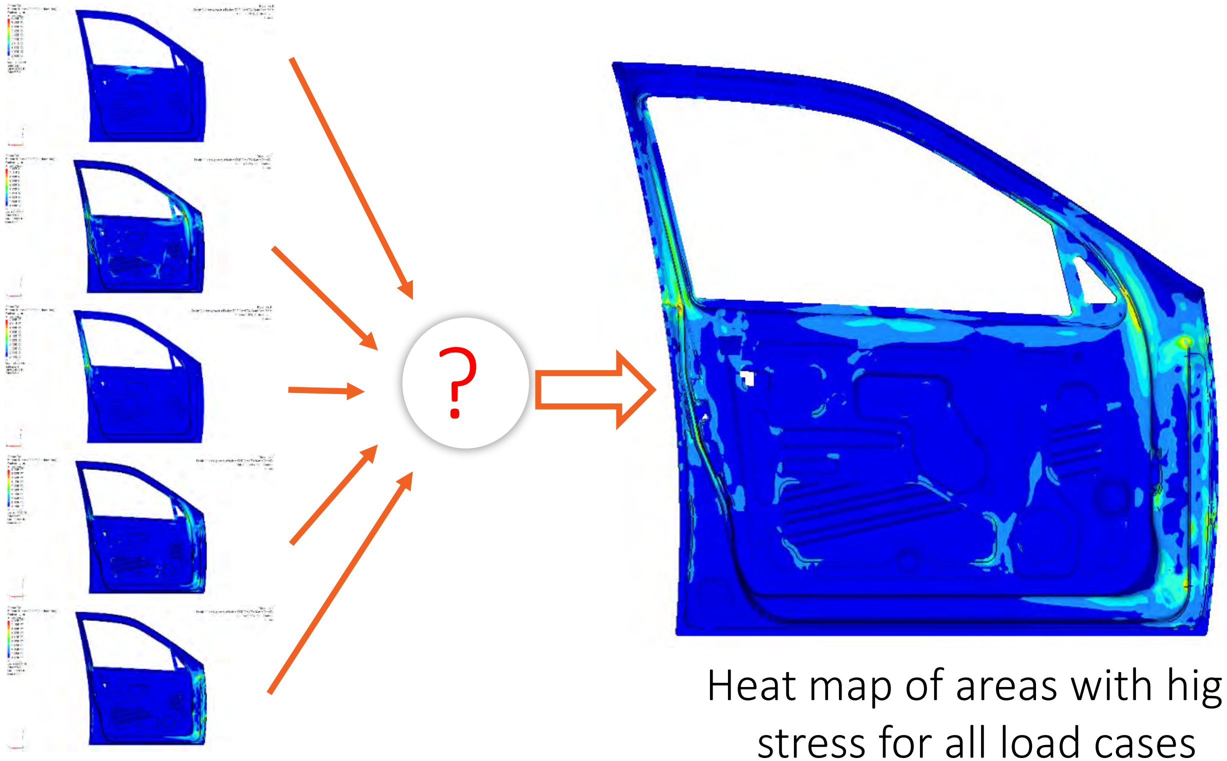
- Manufacturability
- Performance requirement
- Commercial availability

- Performance driven
- Can use FEA optimization to determine laminates

- Performance driven
- Manufacturability
- Can use FEA optimization to determine laminates

Design requirements breakdown

Understanding the influences of induced stress on the door frame.



Heat map of areas with high stress for all load cases

Observations

- The anti intrusion beam contributes to static performances
- Stress on the hinge side of the door is always higher.
- The leading edge of the window frame has very less contribution to stiffness in comparison to the trailing edge.
- The latch side is the second region with high stress concentration.
- The belt line region significantly contributes to door stiffness.

Design requirements breakdown

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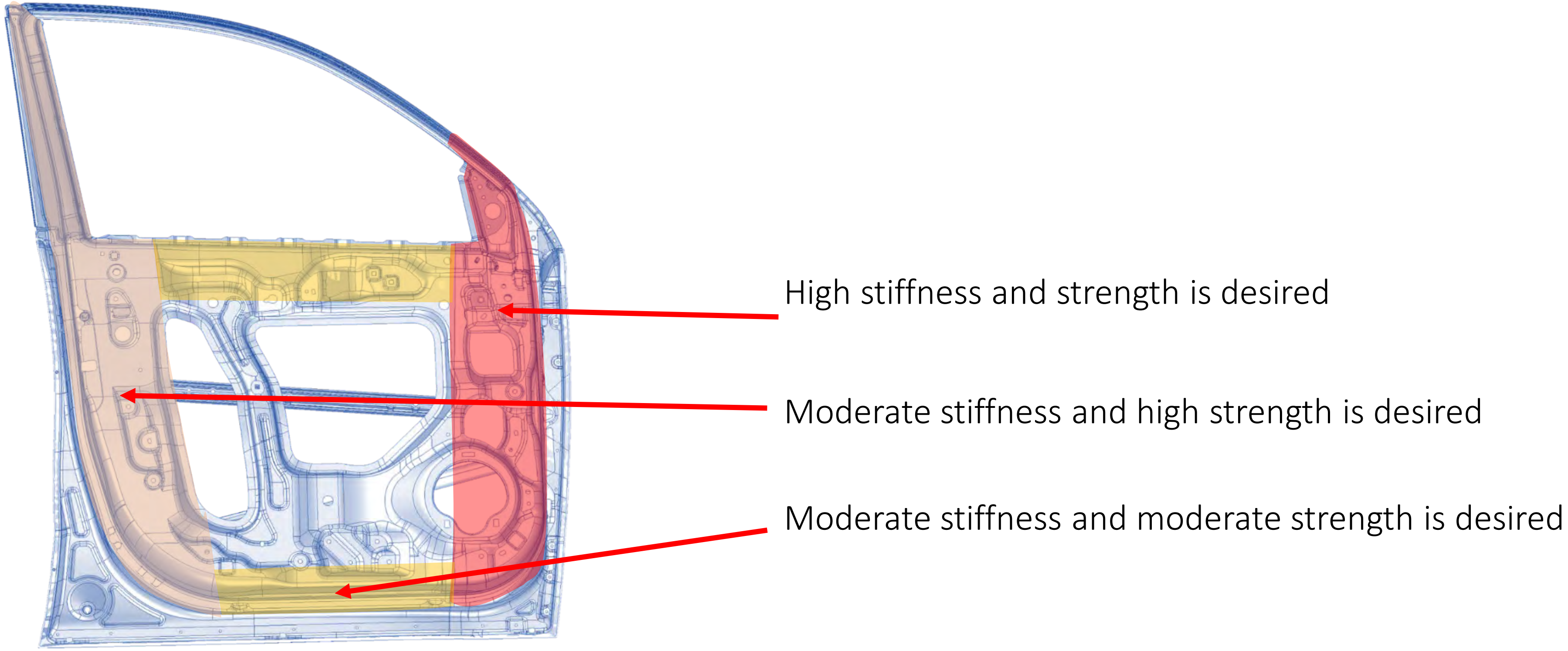
From previous simulations, the door frame was divided into four zones with varying mechanical properties. This information was used for developing design concepts from ground up.



Concept development overview

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Phase 1 Q2 2016	Phase 2 Q2 2016	Phase 3 Q3 2016	Phase 4 Q4 2016
Concept A Concept B	Concept i Concept ii	Concept 1 Concept 2 Concept 3 Concept 4 Concept 5 Concept 6 Concept 7	Concept 2 Concept 4 Concept 7
• Hand drawn sketch. • High level material selection.	• Rough cad models using generic door geometries. • Initial FEA for simple static load cases.	• Design workshop was conducted at CUICAR. • Complete team agreed on 7 concepts for door frame. • Most of these concepts were hand sketched.	• Detailed cad models were generated. • FEA was performed to validate static performance in compliance with Honda's targets.

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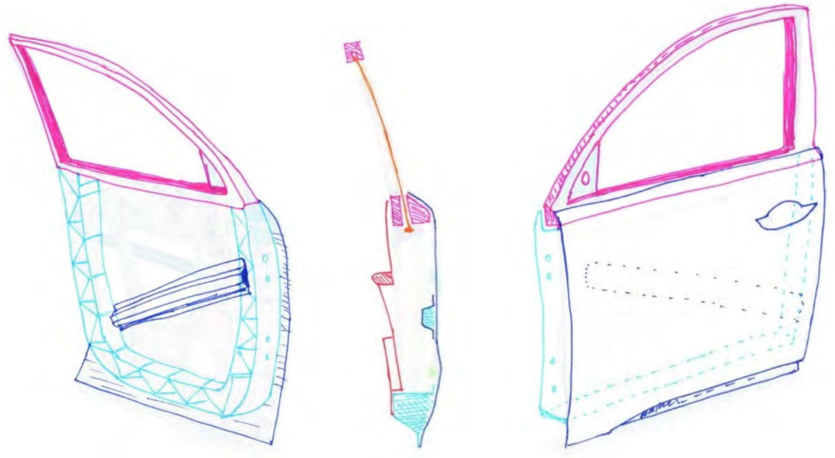
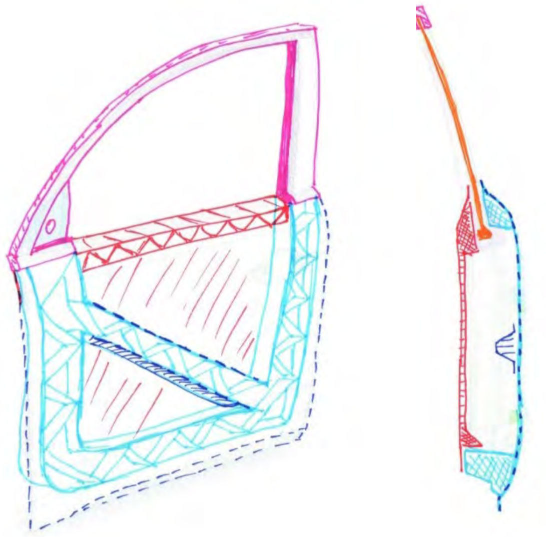
Concept development - Phase 1



Concept A

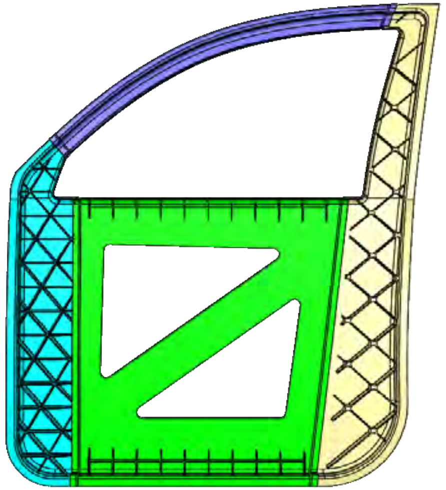
- 4 piece design
- Thermoform outer shell with door cross beam.
- Injection molded window frame with fiber filled CF.
- Non structural inner panel.



Concept B

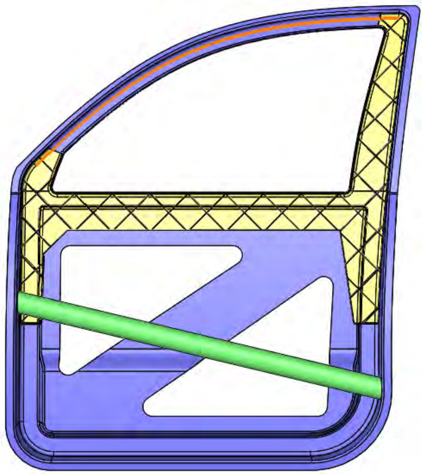
- 3 piece design
- Thermoform outer shell is over-molded with door frame and cross member.
- Injection molded window frame with fiber filled CF.
- Structural inner panel.

Concept development - Phase 2



Concept i

- The frame is split into 4 separate parts
- Easier to injection mold
- Separated based on mechanical strength requirements.
- Rib density can vary depending on load
- Different material systems can be used
- Metal inserts for the hinges are over molded



Concept ii

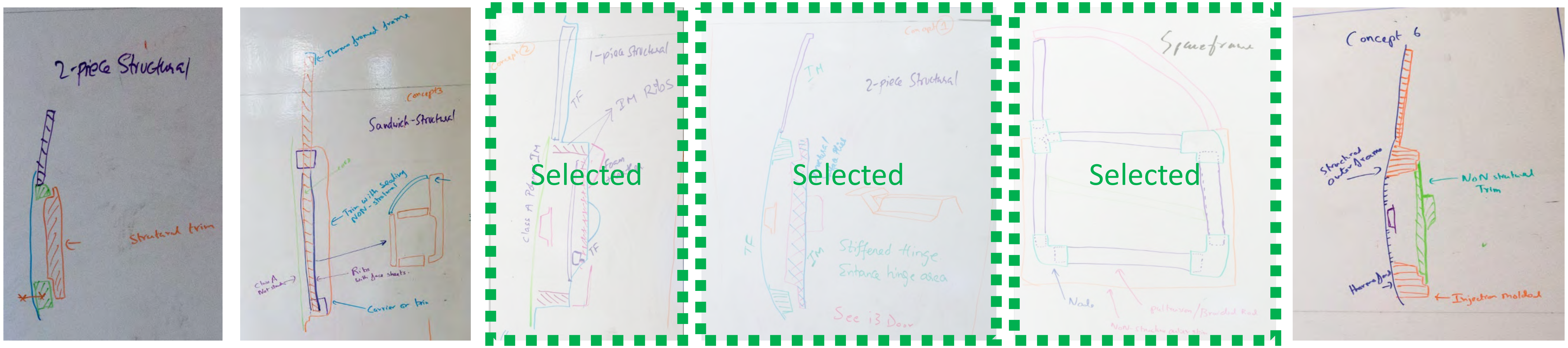
- 3 piece design
- Thermoformed outer shell
- Injection molded reinforcement core
- Injection molded window frame with fiber filled CF.
- Structural inner panel with integrated trim.

Concept development -Phase 3

- Design workshop

  To accelerate concept development a full day workshop was conducted.

  - Faculty and students from Clemson university and University of Delaware participated.
  - Seven unique door concept were generated during this workshop.
  - The team decided not to restrict options in terms of manufacturability.
  - Three most promising concepts were picked for further evaluations.



White board sketches of door frame concepts during the workshop

Concept development - Phase 4

- Detailed design development
  - CAD
    - Accurate design space was used to develop these concepts.
    - All designs will accommodate door internal components.
    - Compatible with current sealing planes of the steel door.
    - Anti intrusion beam in the correct location.
  - FEA
    - Door sag in two open positions .
    - Sash rigidity in two locations on the window frame.

Concept development - Phase 4

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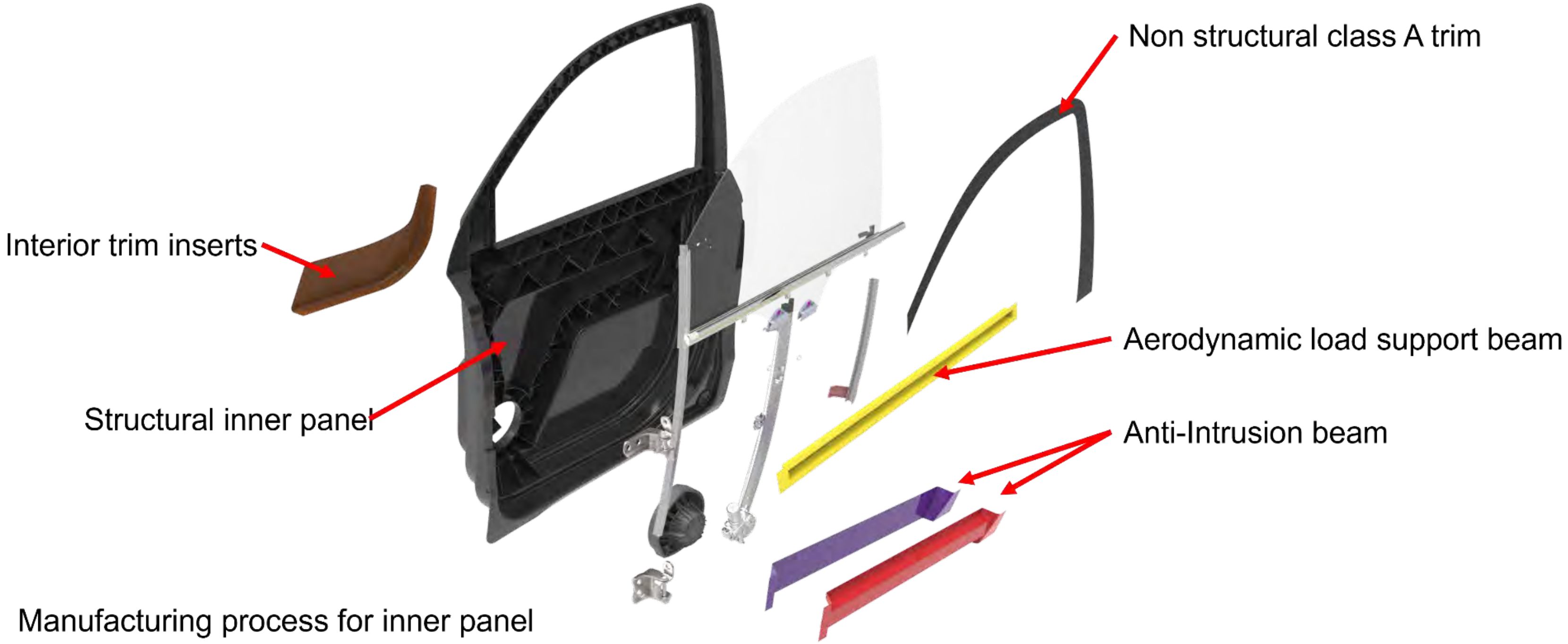
Concept 2

(One piece structural design)

- Inner panel
  - Thermoformed endless carbon fiber panel with over-molded ribs
- Anti-Intrusion beam
  - Thermoformed Endless fiber hat section
- Class A panels
  - ABS injection molded panel (non-structural)



Manufacturing process for inner panel

Thermoformed endless fiber | LFT injection molded ribs | Inner structural panel

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Optimization Concept 2

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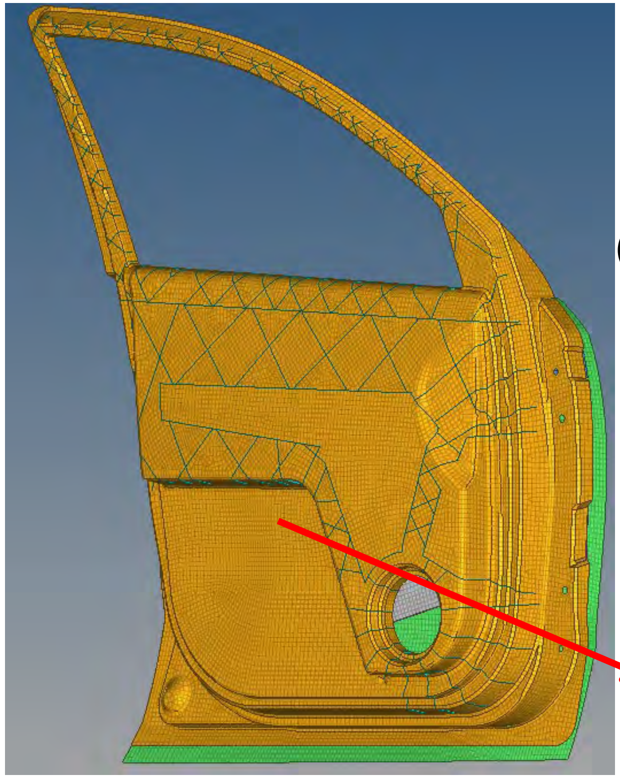
Optimization Concept 2

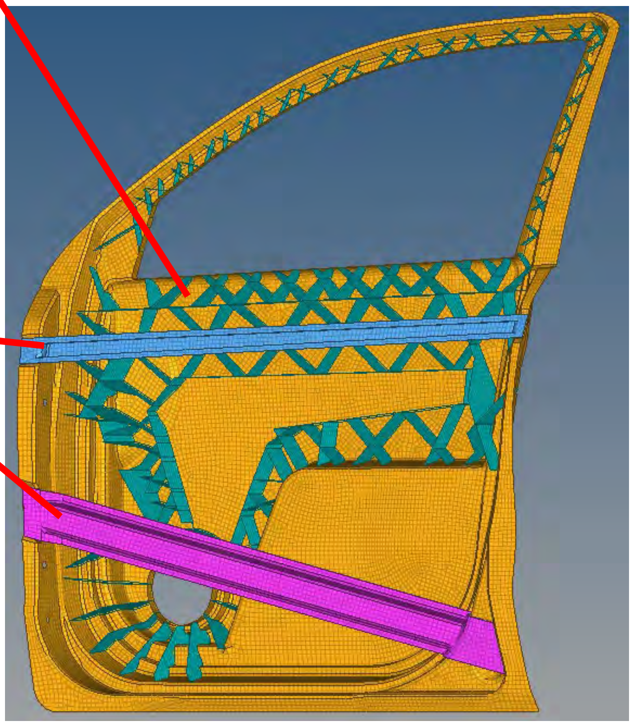
- Initial material setup



Ribs, t=2 mm
LFT with 50% CF

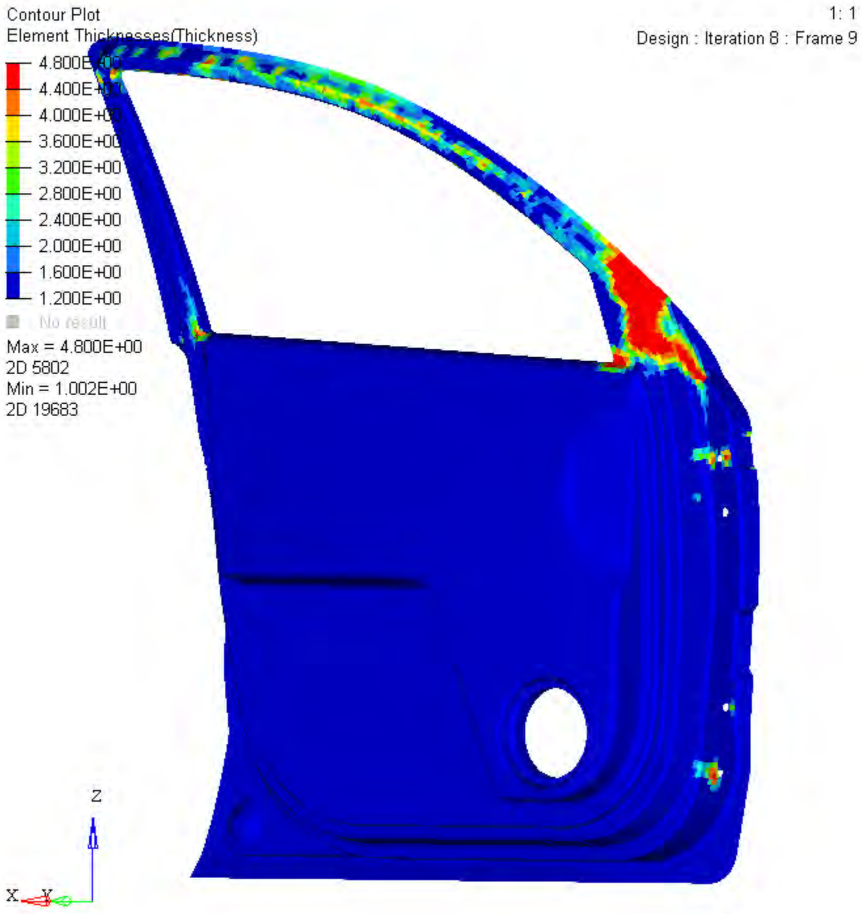
Beams, t=2.4 mm
(Laminate B, Ply t=0.15) mm

Inner panel, t=4.8 mm
(Laminate A, ply t=0.3 mm)



Optimization Concept 2

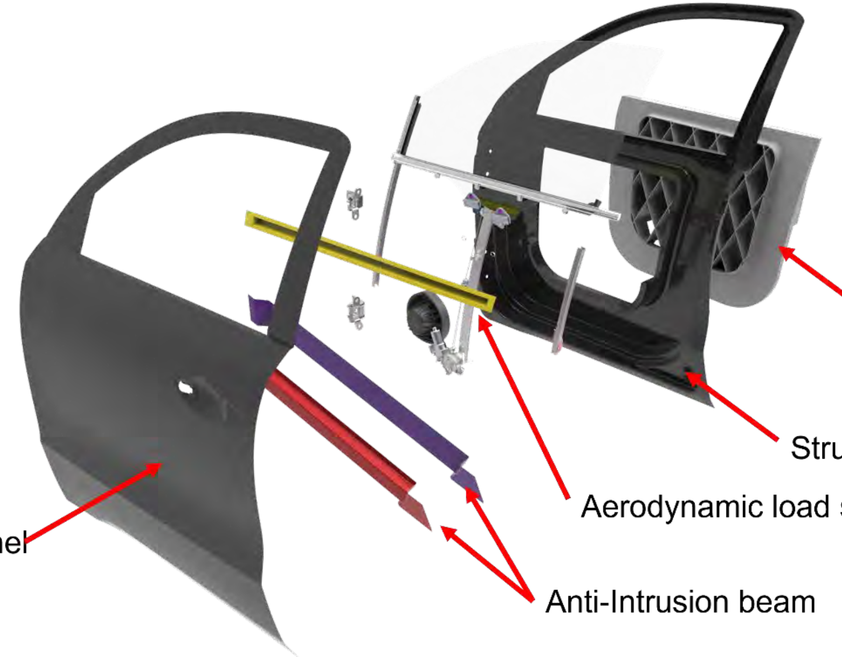
- Laminate thickness plot for optimal design



Concept development - Phase 4

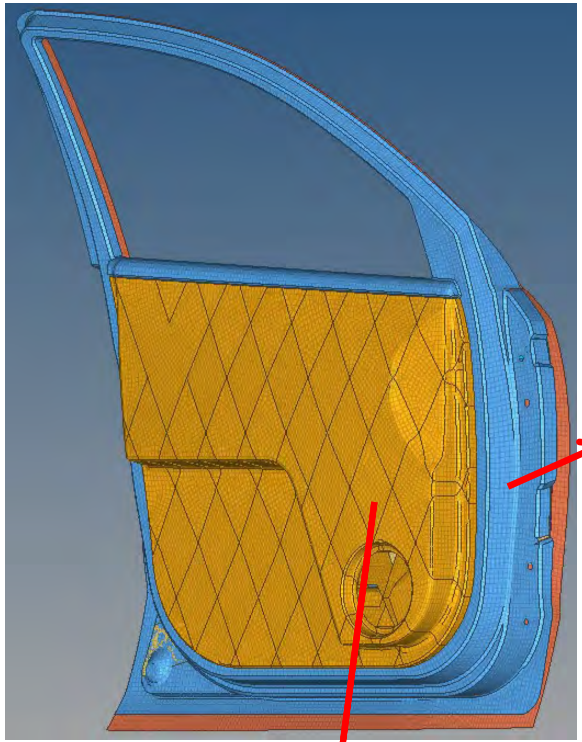
Concept 4 (Two piece structural design)

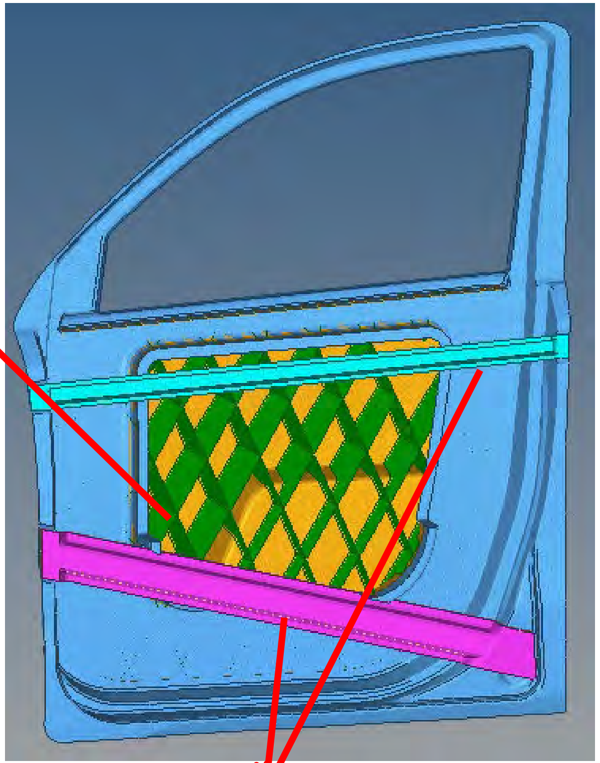
- Inner panel
  - Thermoformed endless carbon fiber panel
- Anti-Intrusion beam
  - Thermoformed Endless fiber hat section
- Class A panels
  - Thermoformed endless carbon fiber panel
- Interior trim
  - LFT carbon fiber injection molded (structural)



Optimization Concept 4

- Optimization Concept 4
  - Initial material setup





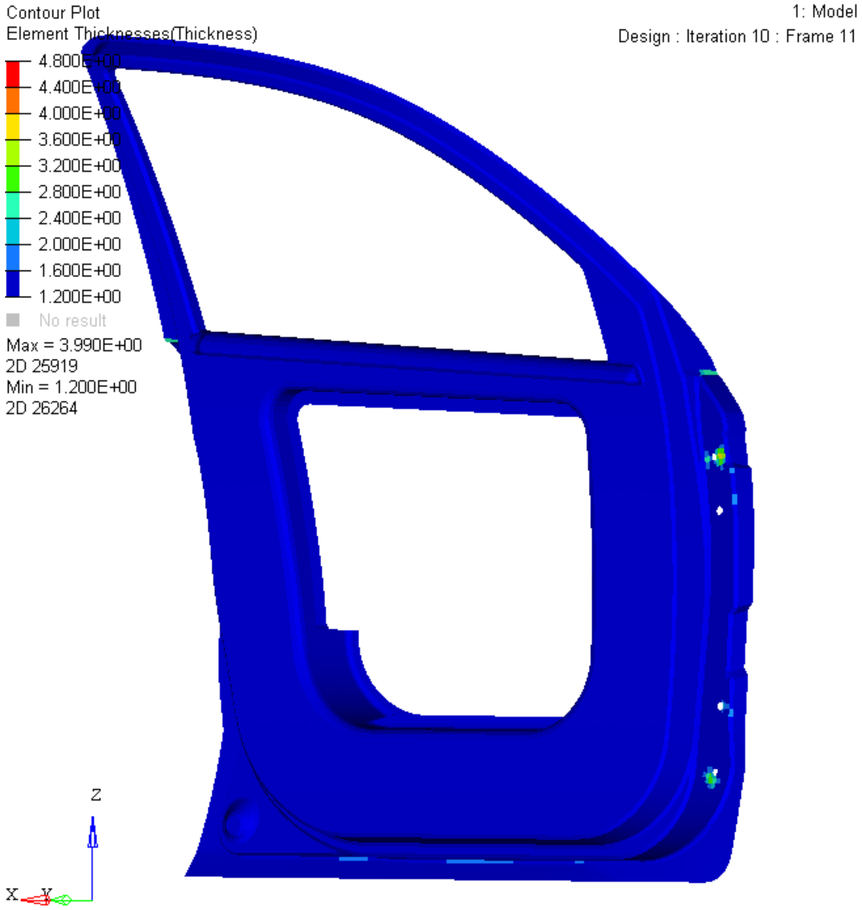
Ribs, t=1 mm
LFT with 50%
CF

Frame,
t=4.8 mm
(Laminate A,
ply t=0.3 mm)

Inner panel,
t=1.5 mm
LFT with 50% CF

Beams, t=2.4 mm
(Laminate B,
ply t=0.15 mm)

- Laminate thickness plot for optimal design

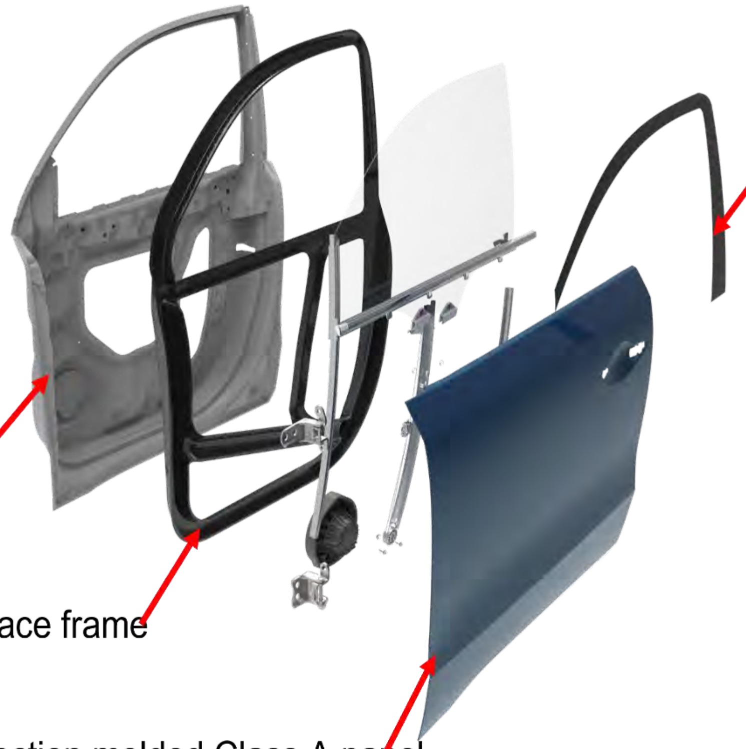


Concept development - Phase 4

Phase 4 – Concept 7

(Space frame design)

- Inner panel
  - Semi structural SFT injection molded
- Space frame
  - Thermoformed Endless fiber hat section
- Class A panels
  - ABS injection molded panel (non-structural)
- Interior trim
  - SFT injection molded (non structural)



Optimization Concept 7

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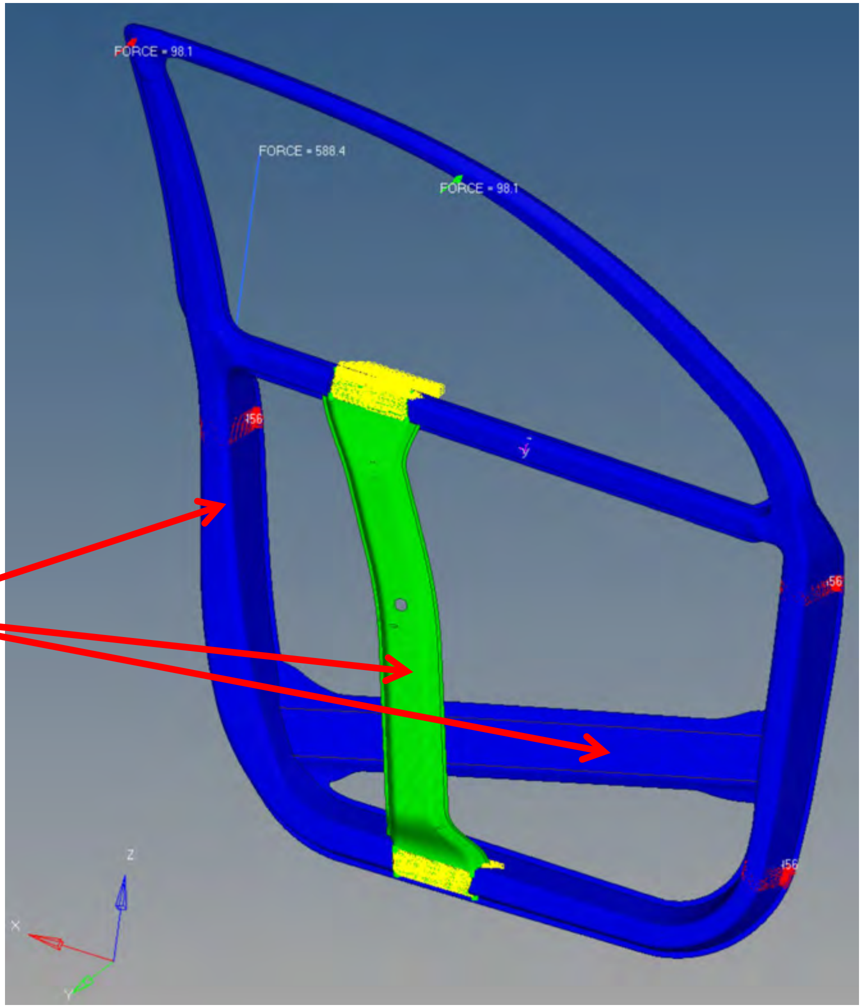
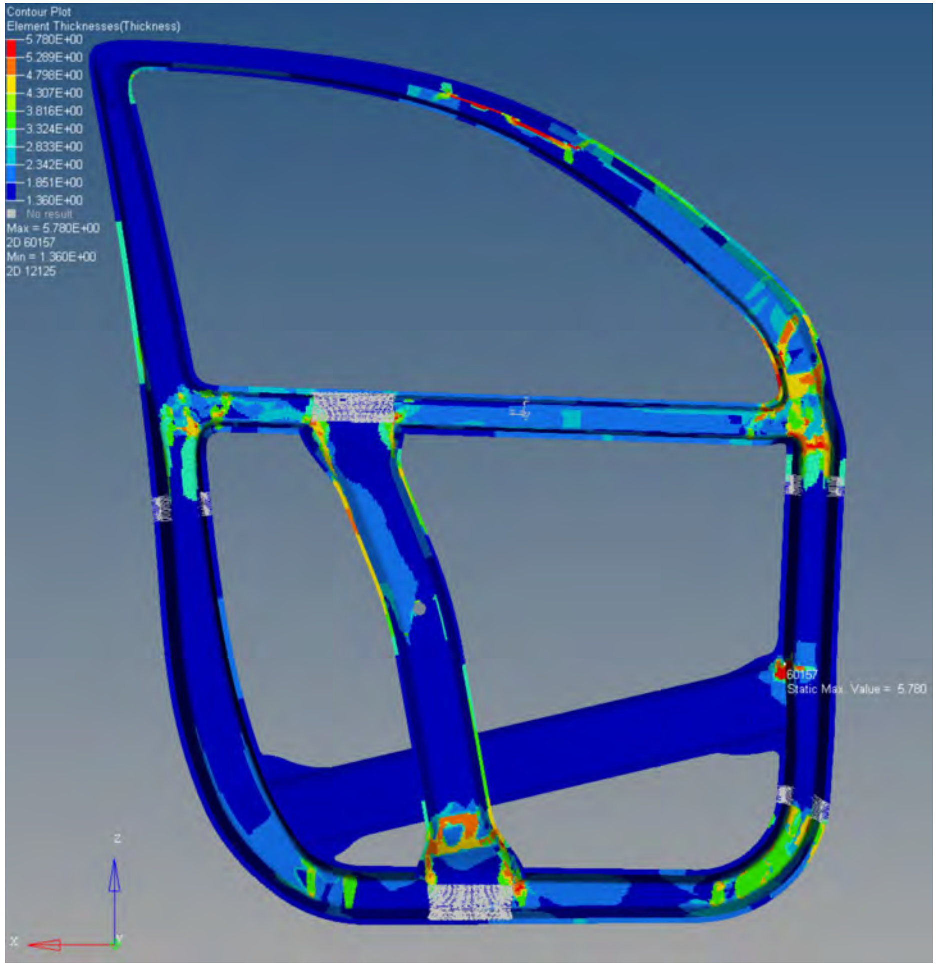
- Initial material setup



All Space elements are set with 5mm laminate with each ply of 0.20 mm

- Laminate thickness plot for optimal design



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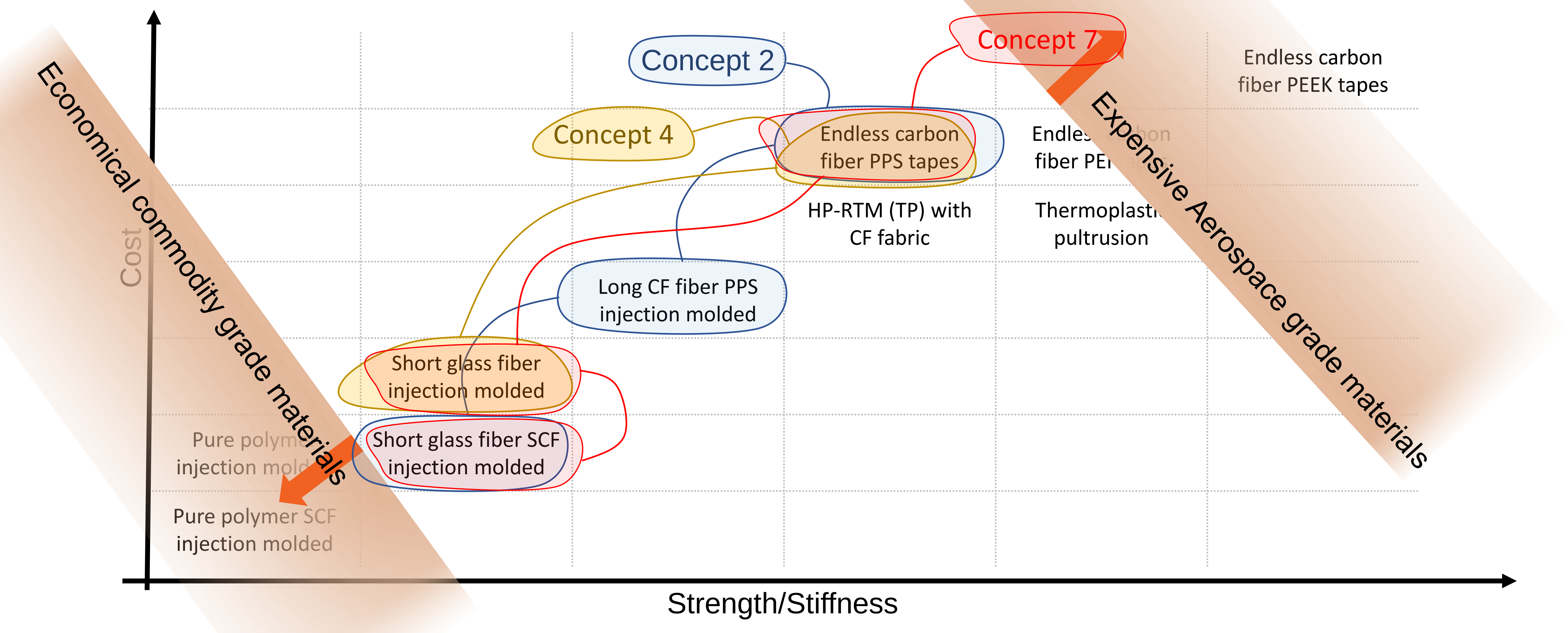
Summary for initial technologies selection



Preliminary Weight Comparison of Concepts

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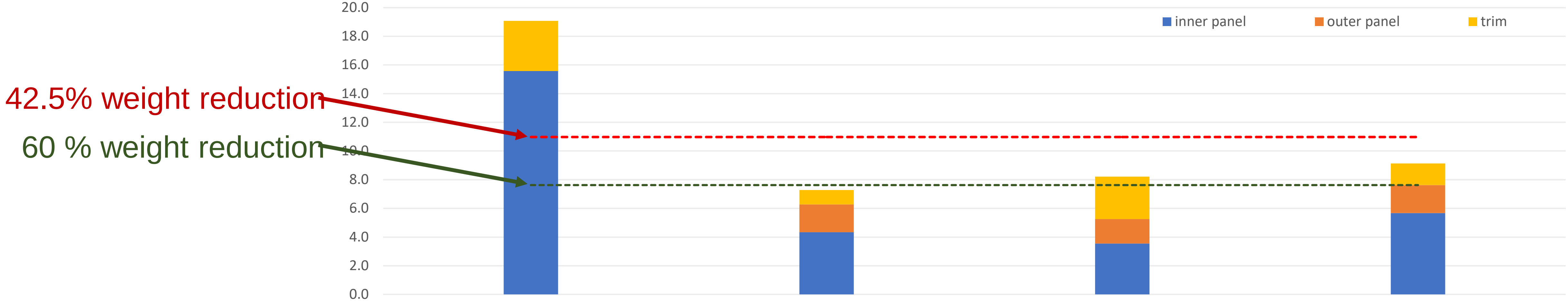

	Baseline (steel)	Concept 2	Concept 4	Concept 7
Structural weight *	19.1	7.3	8.2	9.1
Weight reduction percentage	0%	61.9%	56.9%	52.2%

*Structural weight includes estimates of inner-panel, outer-panel, anti-intrusion beam and interior trim.

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Concept development: Down selection

	Concept 2	Concept 4	Concept 7
			
No.of structural parts in the frame	**1**	**2**	**1**
Exterior Class "A" panel	Removable non-structural	Fixed structural	Removable non-structural
Interior Trim	Integrated into the frame	Semi structural	Non-Structural
Core manufacturing technologies	Thermoforming with over molded LFT	Thermoforming	Injection molding with thermoforming
Parts consolidation potential	Very high	Medium	Low
Easy of assembly	Very Easy	Similar to baseline	Easy

A major issue with Concept 2 was the high number of lazy parts, high estimated cost, and low lightweight potential.

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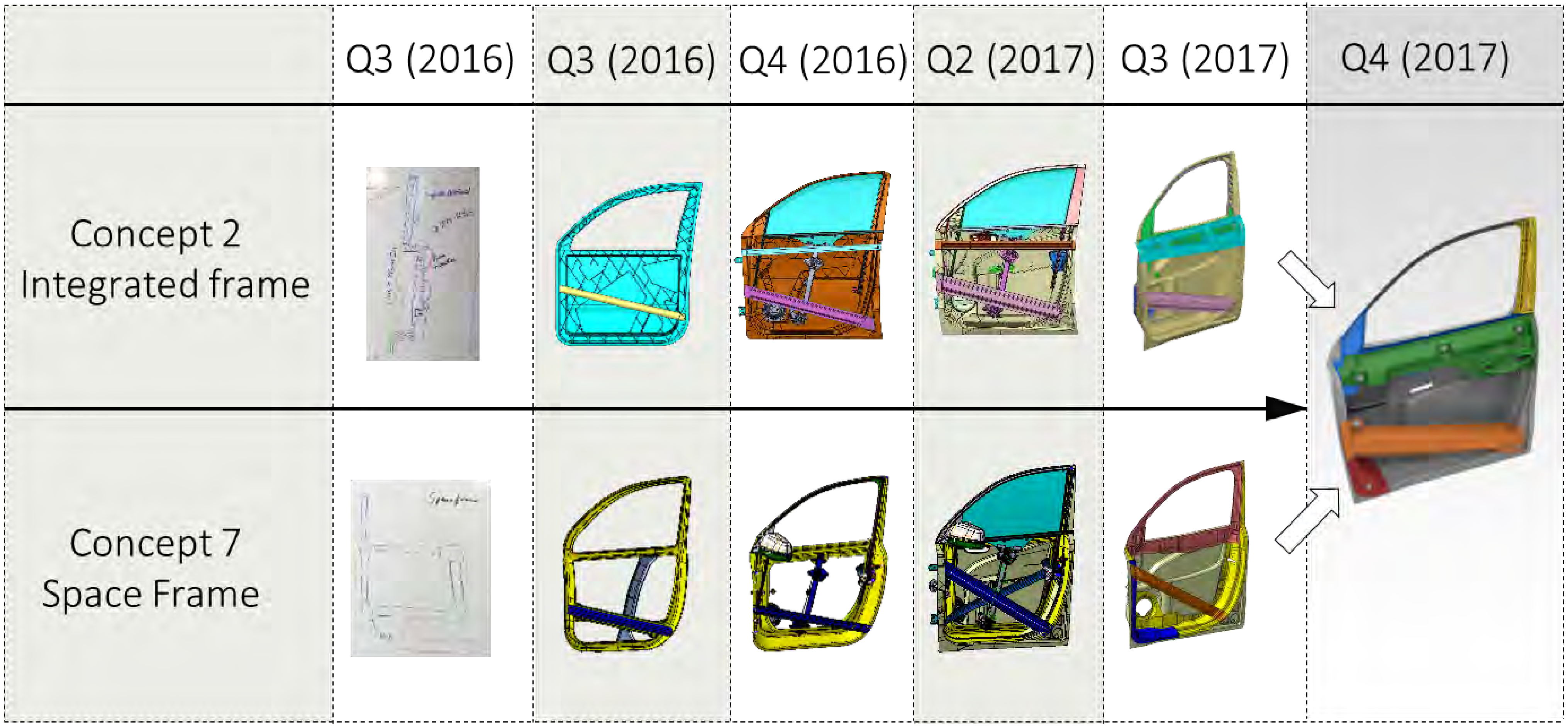
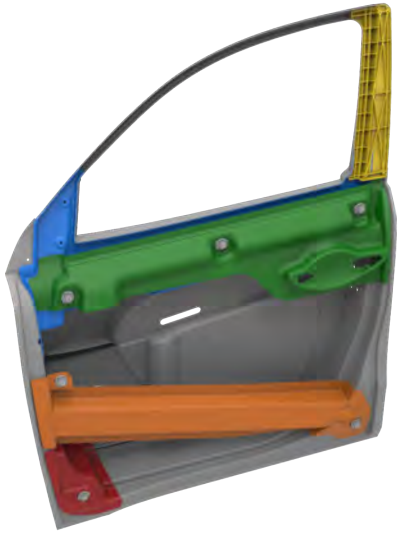
Concept development: Convergence

- The team carefully evaluated both designs and determined that both concepts were converging in many ways to the same fundamental load-bearing design.
- Hence, research continued with Concept 2 to which key findings from Concept 7 were added.

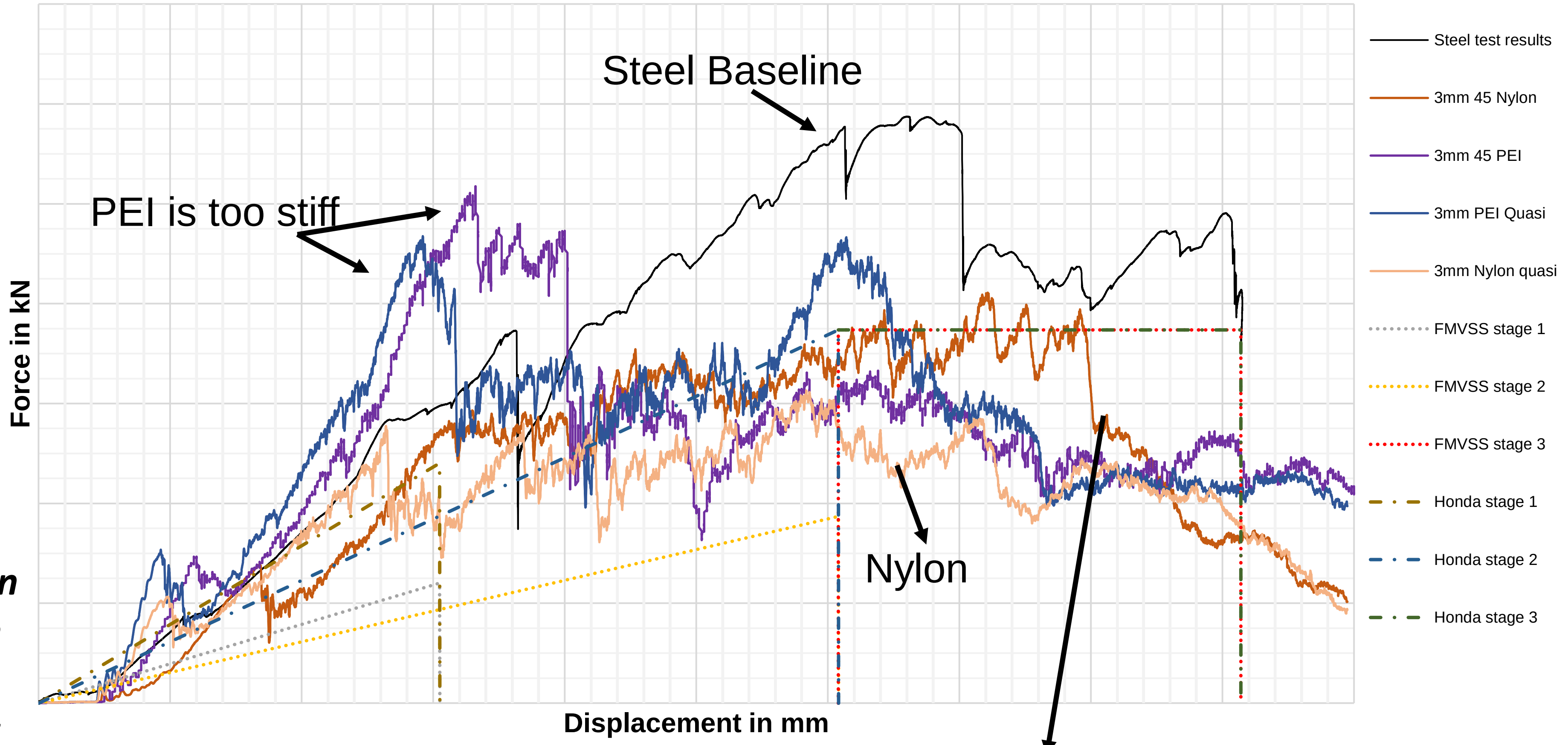


Concept development: Optimization

- In order to achieve the mass reduction target, the team experimented with several different material systems like PEI and Nylon and fiber ply orientations.

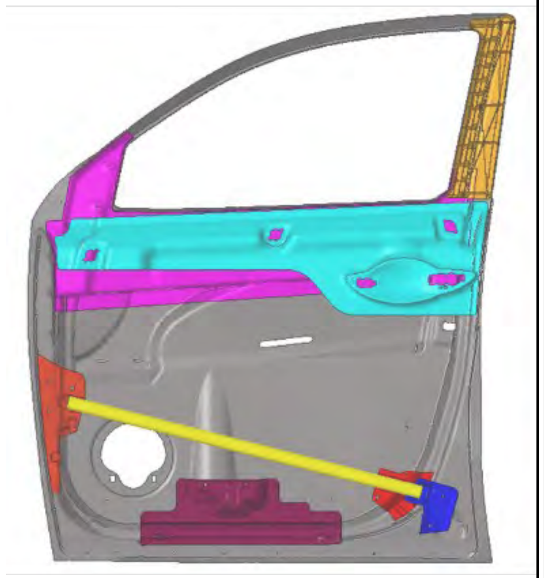
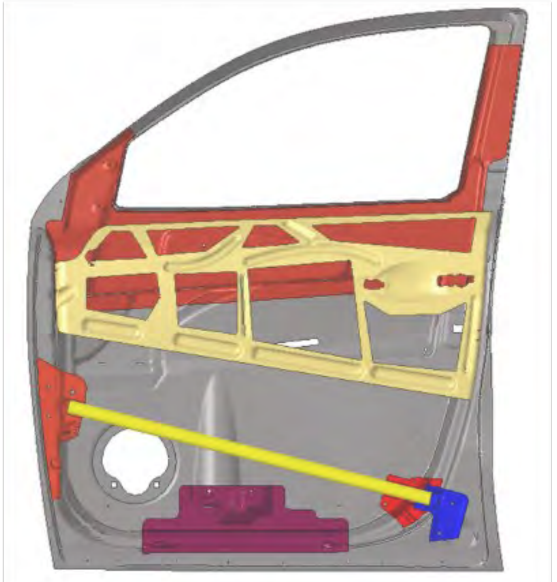
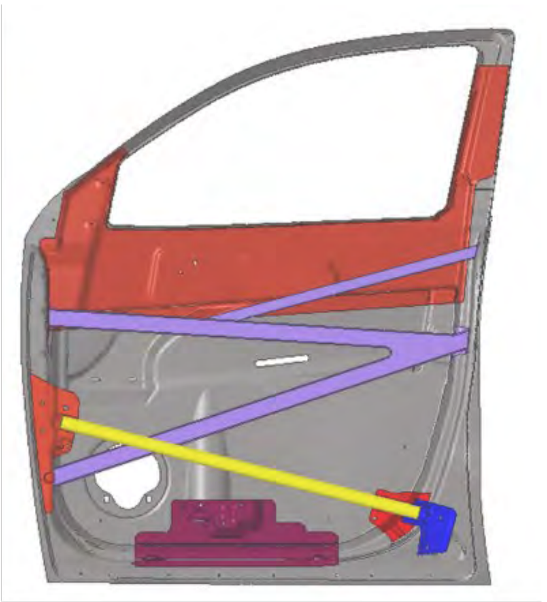
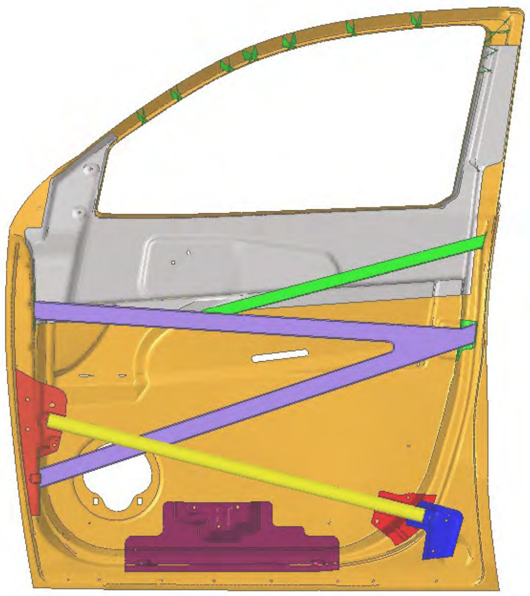


In order to achieve the mass reduction target, the team performed three major revisions in composite door structural design for which several composite optimization, static and dynamic tests were carried out.



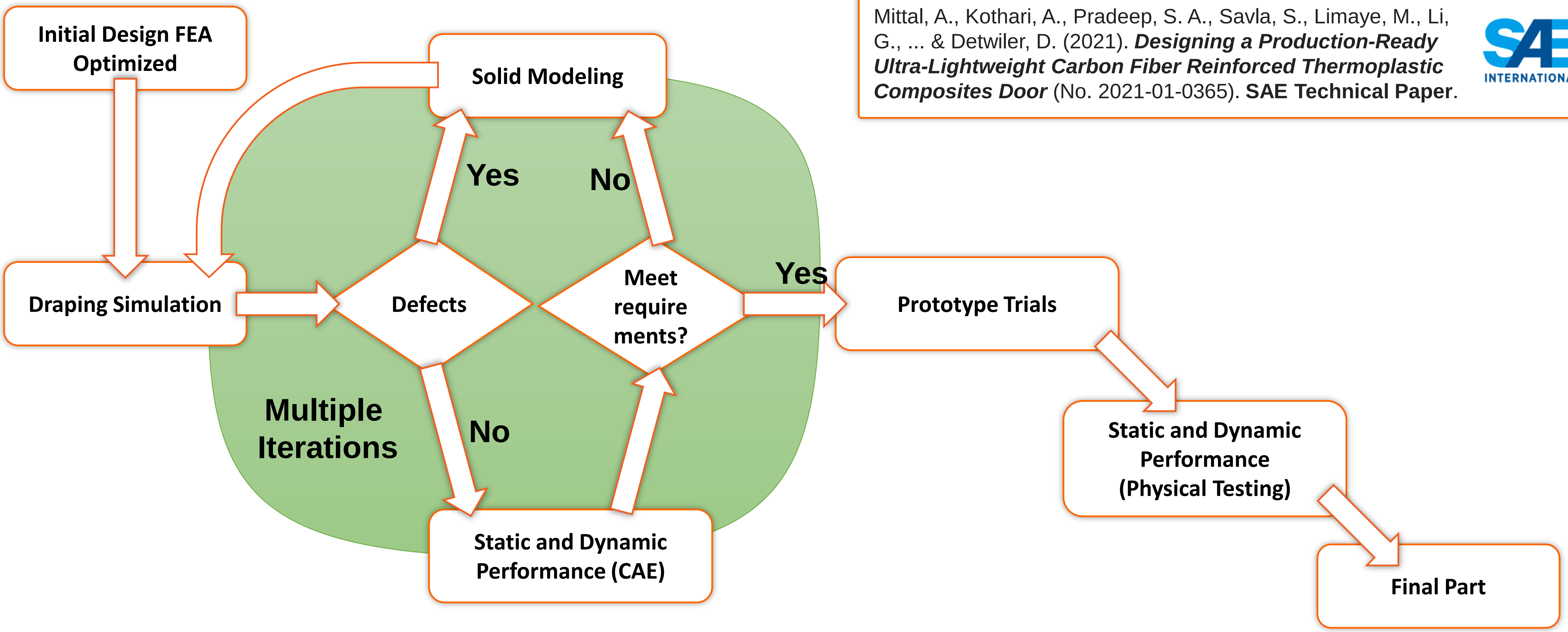
Nylon 45 deforms more plastically than PEI,
But it does not match Honda's baseline target

Concept development: Finalization

2018 (Q12)	2019 (Q13)	2019 (Q14)	2019 (Q15)
			

- First revision removed IM sash region and its replacement with inner beltline stiffener
- Second revision maximized stiffness and manufacturability of outer panel stiffener
- Third revision incorporated topology optimized outer panel stiffener

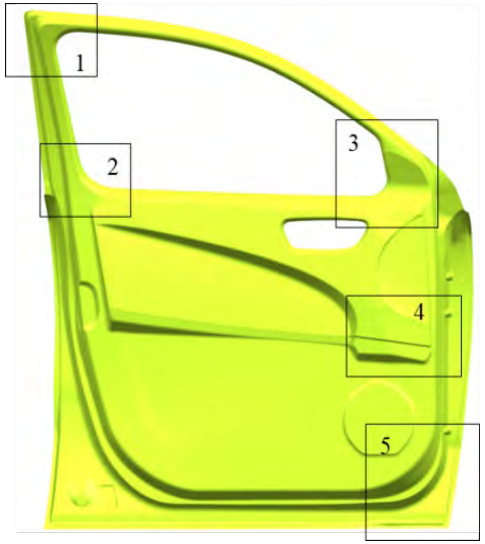
Manufacturing Simulation Inputs for Design

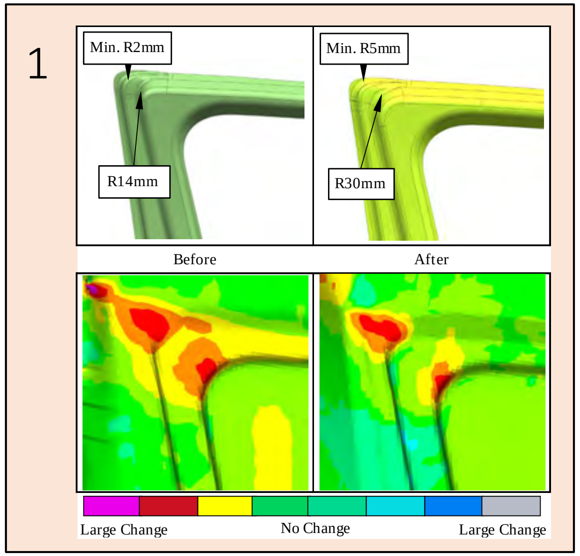


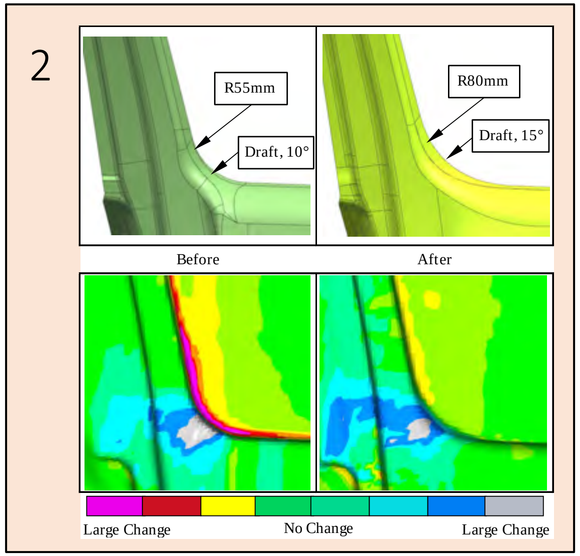
Mittal, A., Kothari, A., Pradeep, S. A., Savla, S., Limaye, M., Li, G., ... & Detwiler, D. (2021). ***Designing a Production-Ready Ultra-Lightweight Carbon Fiber Reinforced Thermoplastic Composites Door*** (No. 2021-01-0365). **SAE Technical Paper**.

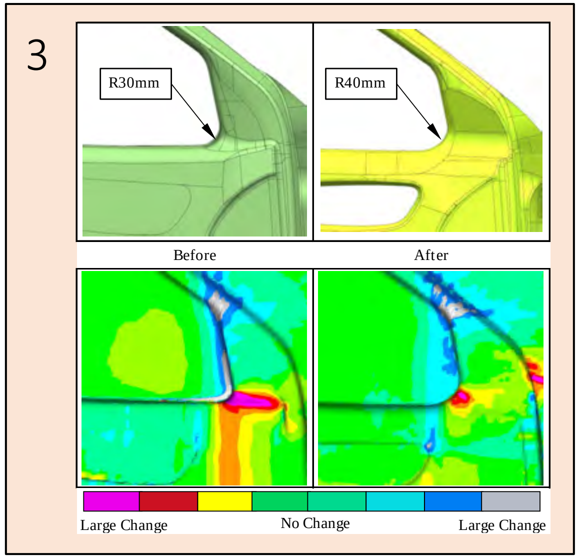
Design optimization for reduction of manufacturing defects using draping simulations with support from Lanxess

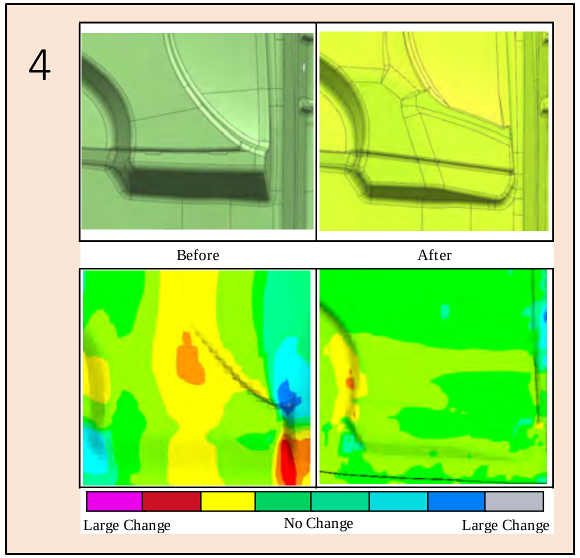
Manufacturing Simulation Inputs





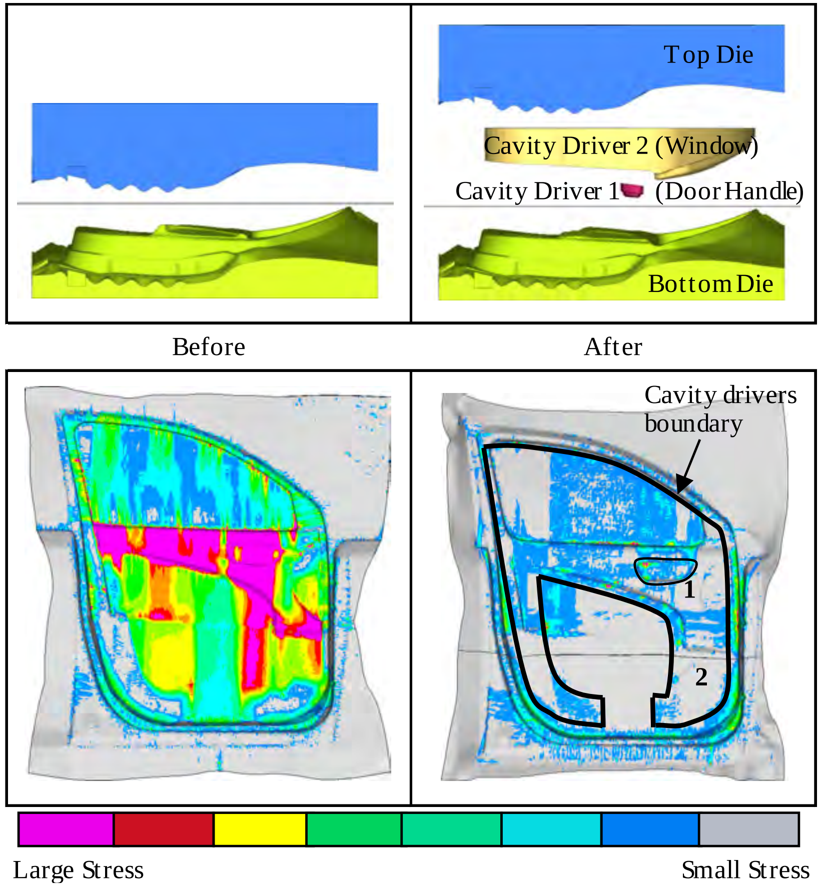






Issue: High shear angle at locations 1-4

Solution: Change in draft angle, radius of curvature, and depth-to-width ratio



Issue: Tearing observed

Solution: Cavity drivers to split single-stage forming into dual-stage forming

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SUMMARY

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

64 % Parts Consolidation

45 % Weight Reduction

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Concluding remarks

- How do we go about exploring the design space with multiple combinations of materials, design geometries and manufacturing pathways?
  - Brainstorming of distinct concepts
  - Iterative improvements towards a converging design
- How do we ensure the right materials are used in the right locations in an efficient manner?
  - Collaboration between material supplier and testing group, design team and the analysis group
- How do we go about the development process as fidelity of information regarding the design and materials' behavior improves?
  - Data-driven approach to making design decisions
  - Qualitative decision making through use of decision matrix

Team and Acknowledgements

- **Dr. Srikanth Pilla (PI)**
- Dr. Gang Li (Co-PI)
- 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

- Anmol Kothari, Madhura Limaye,
- 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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