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

Project ID: mat118

Principal Investigator: Dr. Srikanth Pilla

Department of Automotive Engineering

Department of Materials Science and Engineering

Clemson University

Overview

Timeline

- Start: December 1, 2015
- End: November 30, 2020
- 67% Complete

Budget

- Total project funding
  - $2,249,994 (DOE)
  - $3,117,759 (Cost-share)
- Funding received in FY 15:
  - None
- Funding for FY16
  - $642,819 (DOE)
  - $871,357 (Actual Cost-share)
- Funding for FY 2017
  - $624,023 (DOE)
  - $674,889 (Actual Cost-share)
- Funding for FY 2018
  - $643,023 (DOE share)
  - $760,496 (NON DOE- 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 U.S DRIVE MTT Roadmap report, section 5.1"

Core-Partners

- Clemson University
- University of Delaware
- Honda North America

Relevance - Project Objectives

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 cost increase = [(31.8-18.28)/.453]*5 = $ 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)
- ⚠ In progress - Tooling design (2019; Q3)
- ⚠ In progress - Sub component testing (Fy 2019 Q2)
- ⚠ In progress - Final cost estimation (Fy 2019 Q3)
- 🚫 Not Started - Tool manufacturing (Fy 2019 Q2-Q3)
- 🚫 Not Started - Prototype manufacturing (Fy 2019 Q4)
- 🚫 Not Started - Final door crash testing (Fy 2020 Q2)
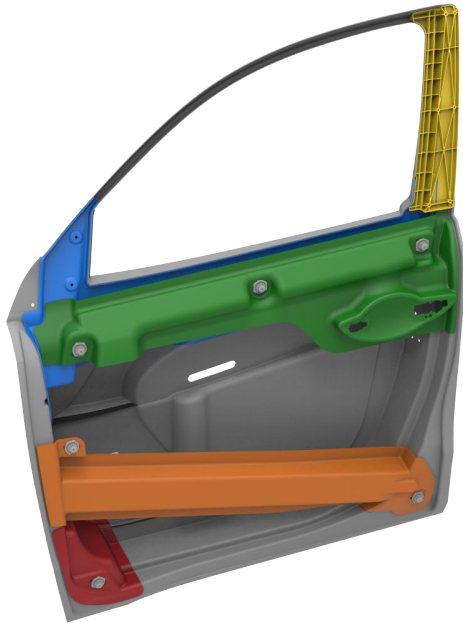
Approach
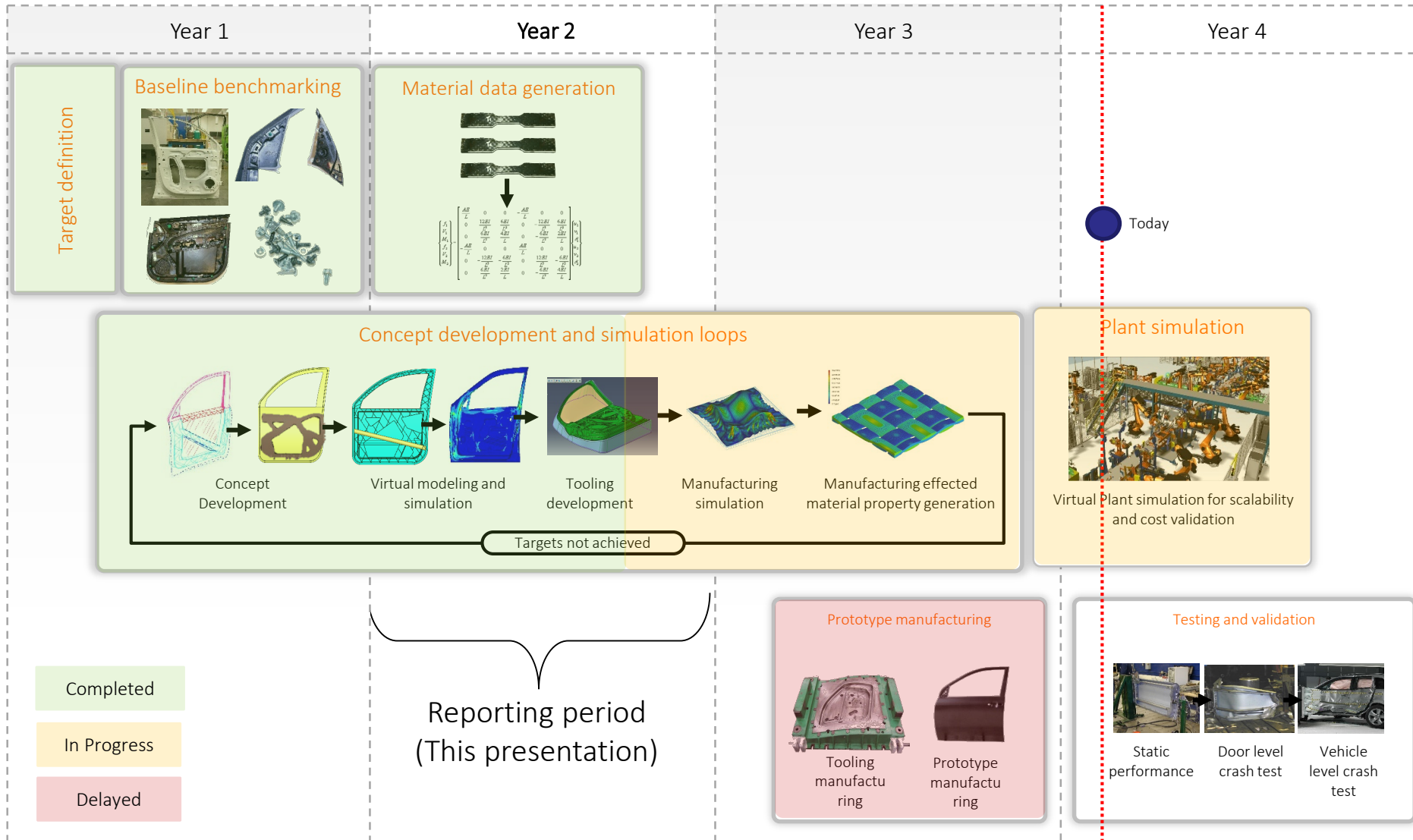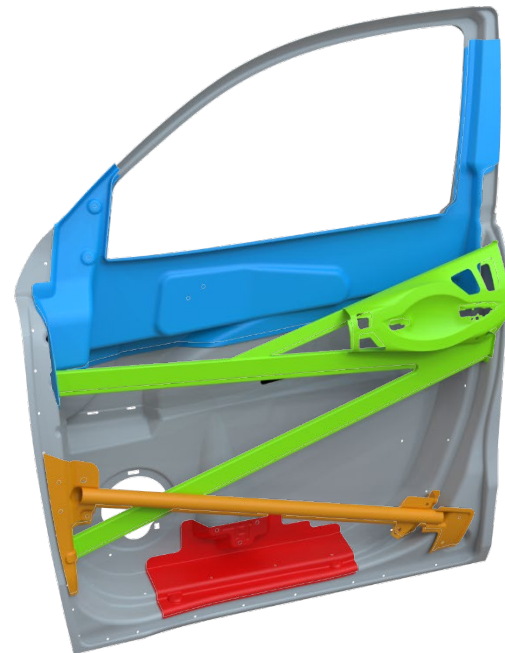
Progress - Design Update

Key changes

- New outer beltline stiffener
- New lower door stiffener
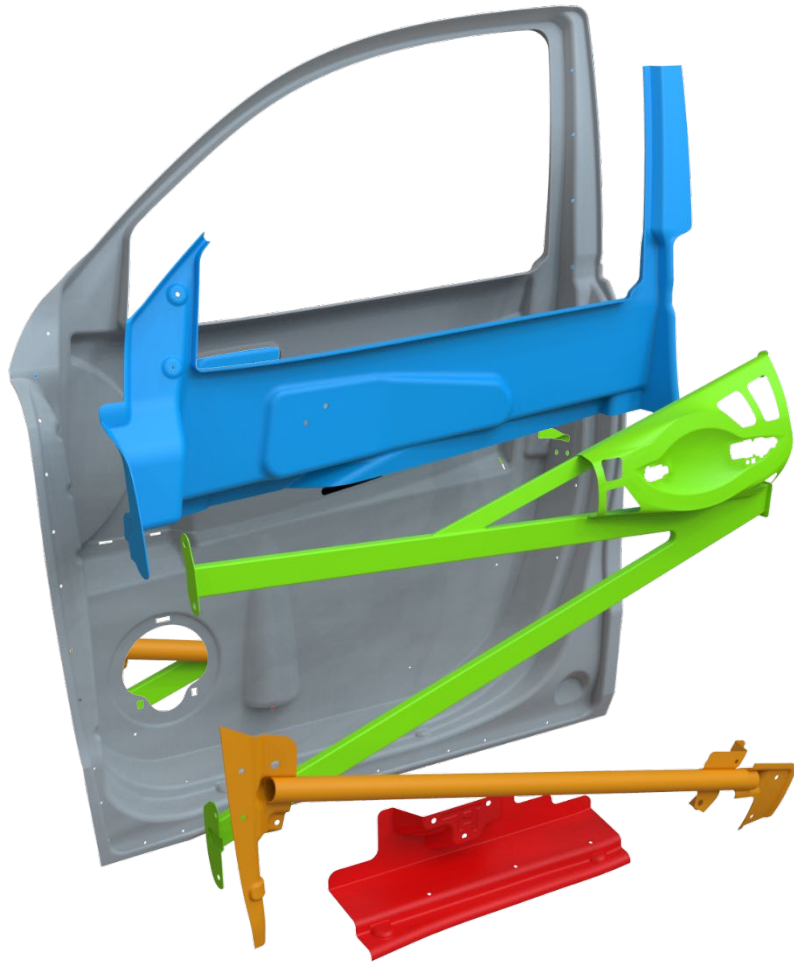- Sash reinforcement integrated into the inner beltline stiffener for part consolidation

Design version 7 - AMR 2018

Design version 11 - AMR 2019

Accomplishments - Concept Development

Structural components of inner panel

Inner frame
- Thermoformed inner panel with integrated trim.
- Material: Woven fabric with UD reinforcements.

Anti intrusion beam
- Hot stamped and welded
- Material: Ultra high strength steel

Inner beltline stiffener
- Thermoformed shell with mounting interfaces for the inner components.
- Material: Woven fabric with UD reinforcements.

Outer beltline stiffener
- Extruded aluminum beams with a stamped handle mount.
- Material: Aluminum 6061

Lower Reinforcement (New Part)
- Stamping
- Material: Aluminum 6061

Accomplishments – Concept Development

Outer panel design update.

- Added reinforcement to the injection molded outer panel for preventing oil-caning, and improving stiffness for aerodynamic loads
- Reduced wall thickness from 2.2 mm to 1.2mm
- Almost no impact on weight

Design version 7 - AMR 2018	Design version 11 - AMR 2019

Accomplishments – Fit and Function Validation

Validating the composite door for fit and function.

- Using low cost prototyping methods manufactured a thermoset door to verify fit, sealing and latching of the composite door on the existing body structure

- 3D printed inner belt line stiffener, outer belt line stiffener and lower reinforcement and assembled to validate door internal packaging
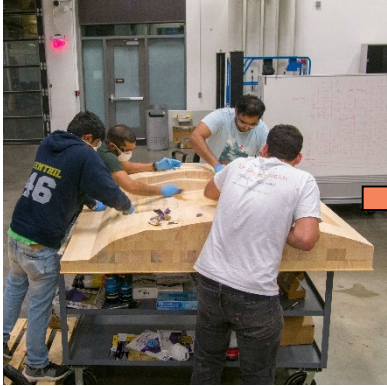
1.Prepping wooden negative tool.

2.Carbon fiber hand layup for vacuum infusion.

3.Test fit CFRP door frame in Acura MDX

4. 3D printed door components for geometric evaluation.

Accomplishments - Fit and Function Validation

Summary of the fit and function

✔ All sealing planes for the composite door match the existing body structure

✔ The hinge, latch and limiter pickup points on the body structure match the composite door

✔ All door internal components fit and function in the door

⚠ The map pocket interferes with the B-pillar interior trim; map pocket is currently redesigned to prevent the interference.
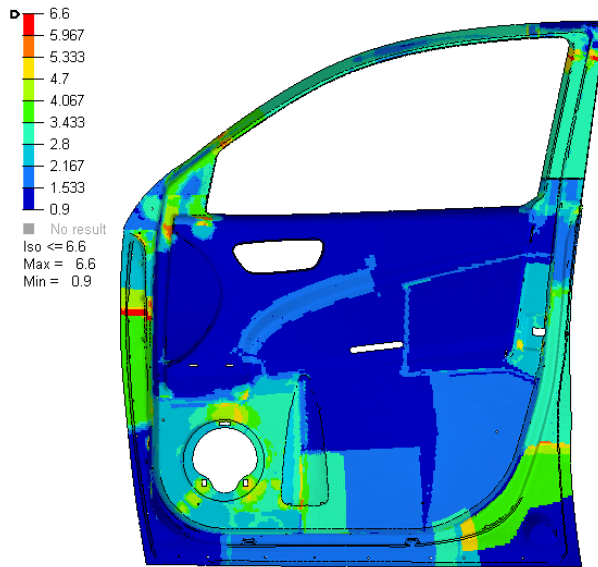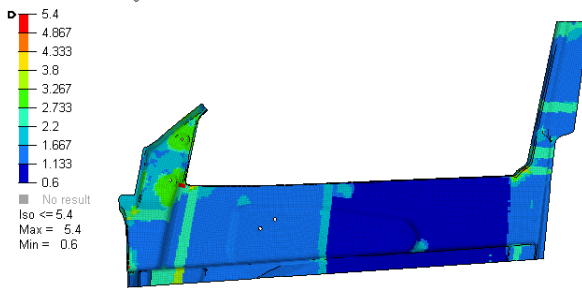
Static performance (daily use and misuse)

- These linear load cases represent door performance for daily use and occasional misuse
- These targets are used for optimizing the composite ply configurations

| Targets				Baseline Door	Composite Door (V11)
Structural frame mass	<	7.26	Kg	15.1	8.3
Door Sag - Fully open	<	5	mm	3.5	2.89
Sash Rigidity at point A	<	3.5	mm	0.93	2.9
Sash Rigidity at point B	<	4	mm	0.91	2.29
Beltline stiffness-Inner panel	<	1.5	mm	1.34	0.59
Window regulator (Normal)	<	1	mm	6.88	0.73
Mirror Mount rigidity in X	<	0.92	mm	0.57	0.92
Mirror Mount rigidity in Y	<	2.25	mm	0.86	0.97
Door Over opening	<	Baseline	mm	24.7	18.52
Speaker mount stiffness	<	Baseline	mm	0.35	0.18

Accomplishments - Structural Performance

Three crash test modes were selected to evaluate the crash performance of the composite door as suggested by our OEM partner
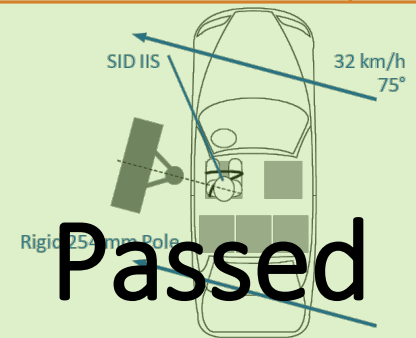
1. FMVSS 214s

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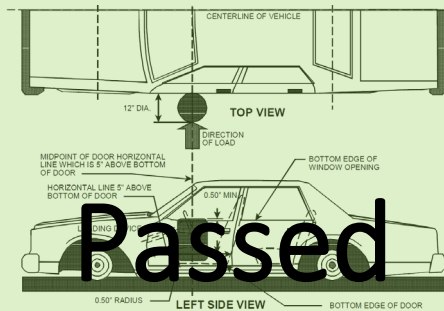
A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

2. IISH SI MDB(DB)

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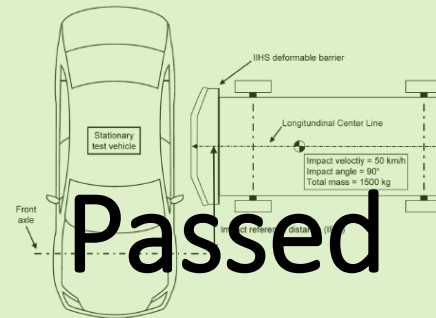
A moving deformable barrier is impacted with a stationary vehicle at 50 km/h.

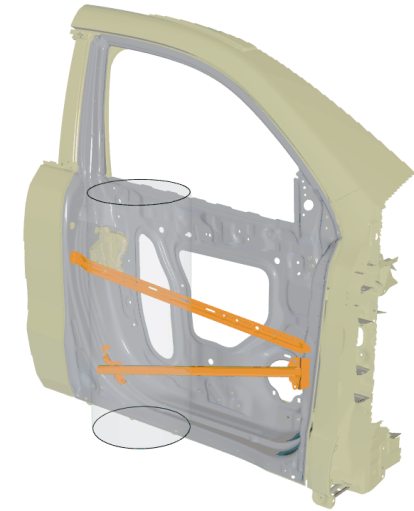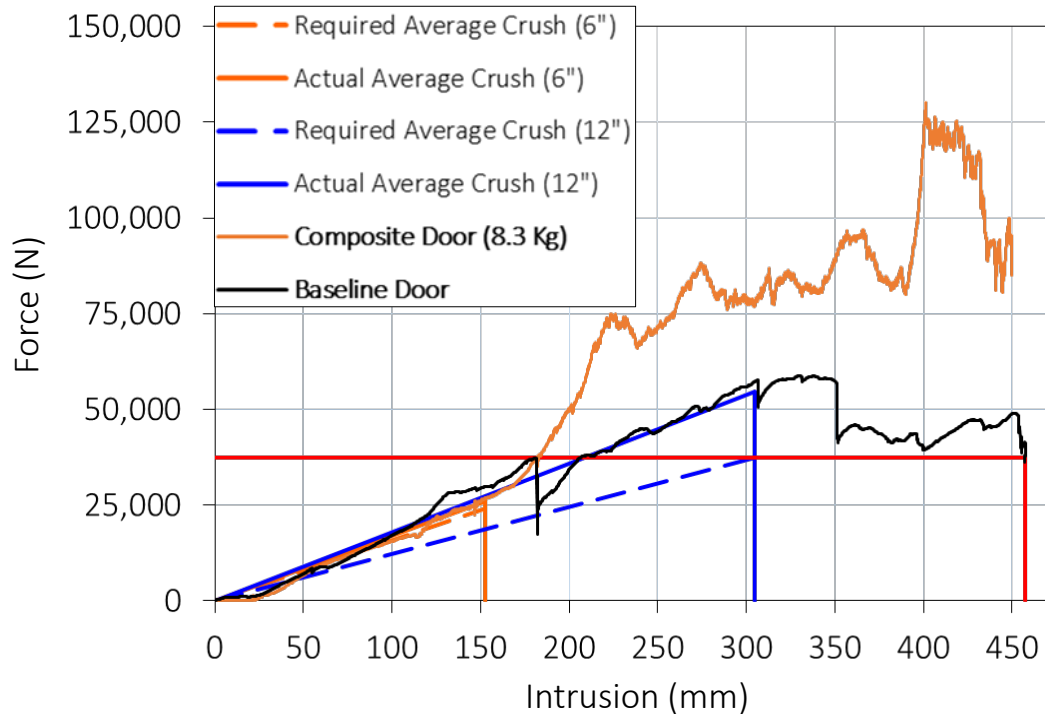## 3. FMVSS 214 (RP)

Passed

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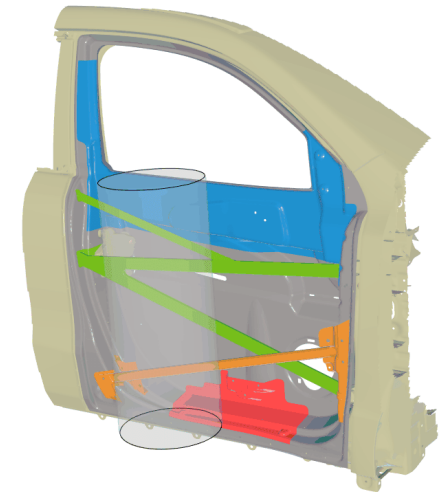
Accomplishments - Crash Performance

FMVSS 214: Quasi static pole test

- Has higher force response than baseline steel door.

- Significant crush resistance is offered even after the inner panel fails.

Baseline steel door

Composite door

Accomplishments - Crash Performance
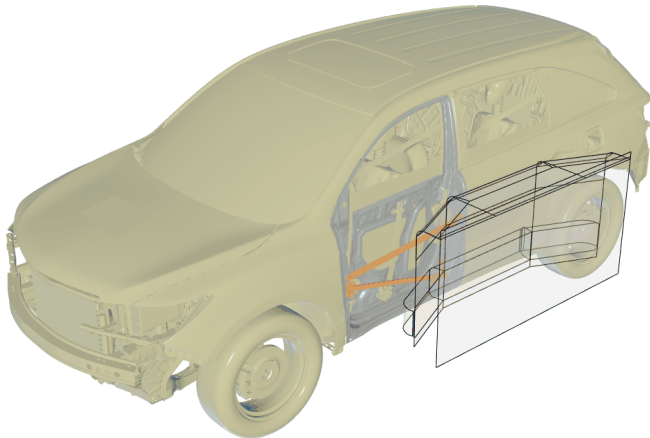
IIHS side impact protocol (MDB: Version 4)

- The moving deformable barrier (MDB) impacts the car perpendicularly. Such configuration together with the barrier bumper height makes this test more challenging than FMVSS 214

- The impact speed is 50 km/h and the impact mass is 1500 kg

- The composite door outperforms the baseline steel door

Baseline steel door

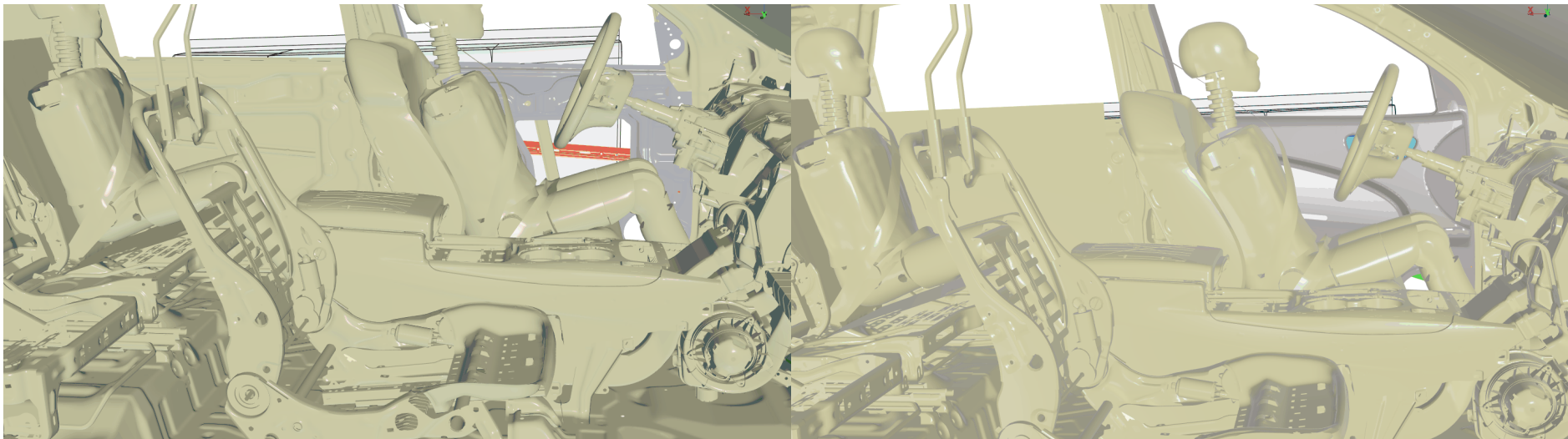Composite door
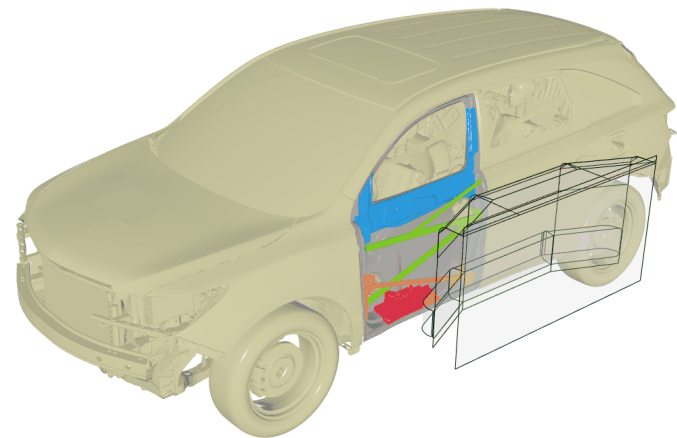
Accomplishments - Crash Performance

Gauging metrics for IIHS SI- MDB

- **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	Baseline [mm]	Composite [mm]	Difference [mm]	Difference [%]
Occupant survival space	134.3	140	5.7	4.2%
Maximum intrusion at roof	62.1	48.16	-13.94	-22.45%
Maximum intrusion at window sill intrusion	279	233	-46	-16.5%
Intrusion at hip location of the dummy	175.6	125.64	-49.36	-28.1%
Maximum intrusion at lower door region	210.4	205.76	-4.64	-2.2%

Baseline steel door

Composite door

Accomplishments - Crash Performance

FMVSS 214 rigid pole

- In this crash mode, the vehicle is mounted on a mobile platform and is impacted with a rigid pole at 75° to the length of the vehicle

- 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
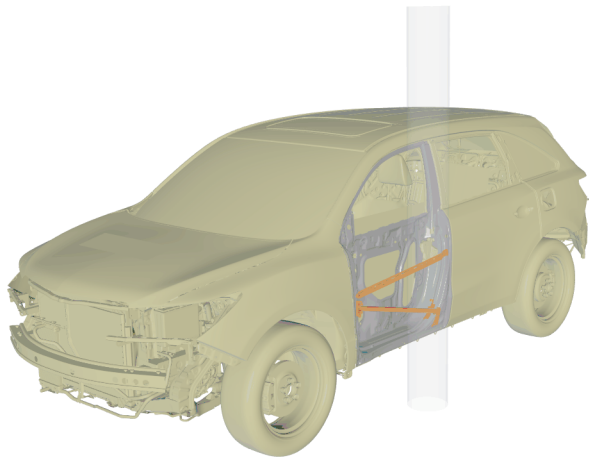
Composite door
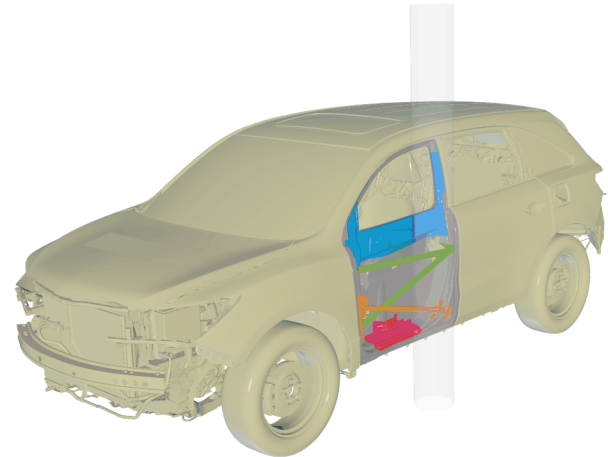
Accomplishments - Crash Performance

Gauging metrics for FMVSS 214 rigid pole

- 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	Baseline [mm]	Composite [mm]	Difference [mm]	Difference [%]
Maximum intrusion at B-pillar	150.9	164	13.1	8.68%
Maximum intrusion at sill intrusion	293.4	287.6	-5.8	-1.98%
Maximum intrusion at roof	254	259.8	5.8	2.28%
Maximum intrusion at window sill intrusion	434.5	438.1	3.6	0.83%
Intrusion at Hip location of the dummy	355.3	336.5	-18.8	-5.29%
Maximum intrusion at lower door region	440.3	443.1	2.8	0.64%

Baseline steel door
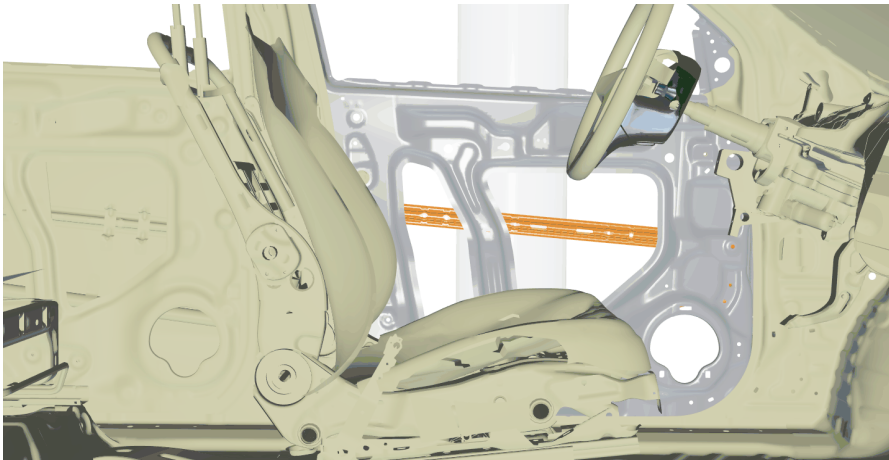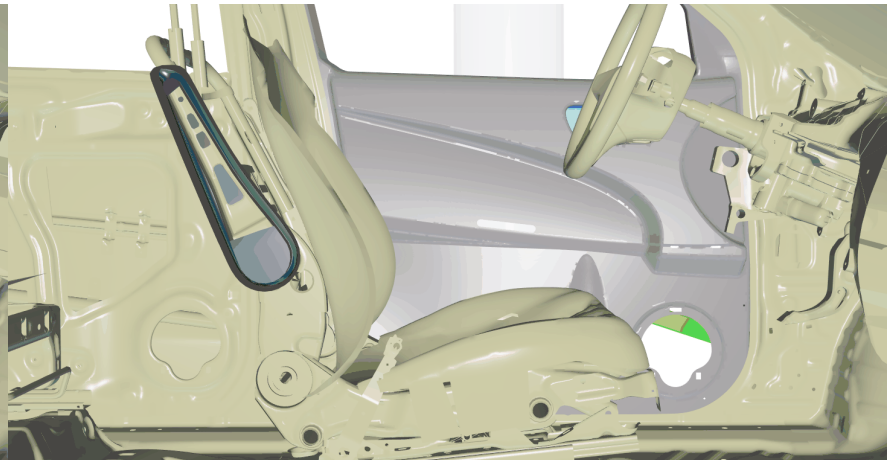
Composite door

Accomplishments - Manufacturing Simulation

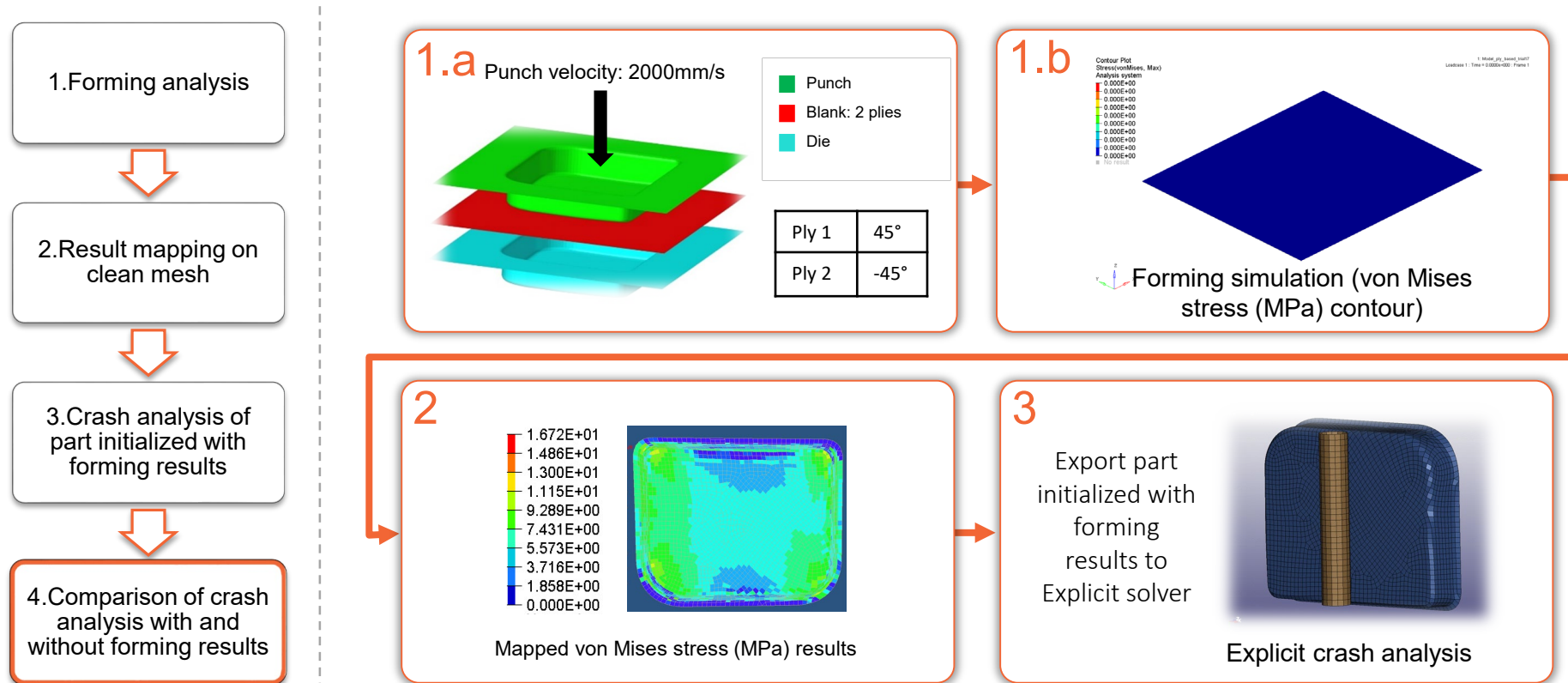## Predicting manufacturing induced effects on mechanical performance

- The residual stress induced during forming have direct impact on crash performance of the composite structure

- To minimize this risk, a novel simulation/optimization pathway is used to predict the manufacturing induced property reduction

1.Forming analysis

2.Result mapping on clean mesh

3.Crash analysis of part initialized with forming results

4.Comparison of crash analysis with and without forming results

1.a
Punch velocity: 2000mm/s

🟩	Punch	
🟥	Blank: 2 plies	
🟦	Die	

Ply 1	45°
Ply 2	-45°

1.b

Contour Plot
Stress(vonMises, Max)
Analysis system

Forming simulation (von Mises stress (MPa) contour)

2

1.672E+01
1.486E+01
1.300E+01
1.115E+01
9.289E+00
7.431E+00
5.573E+00
3.716E+00
1.858E+00
0.000E+00

Mapped von Mises stress (MPa) results

3

Export part initialized with forming results to Explicit solver

Explicit crash analysis

Accomplishments – Manufacturing Simulation

Comparison of crash performance with and without mapping manufacturing induced residual stress
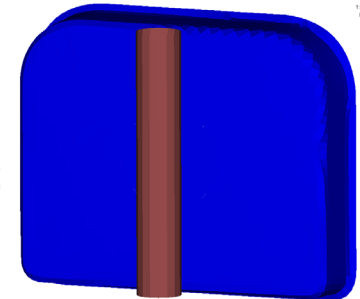
- A 11% reduction in energy absorption capacity was observed after mapping the residual stress.

- This simulation pathway will help to account for performance loss due to manufacturing process and also optimize the tooling design to minimize the performance losses.

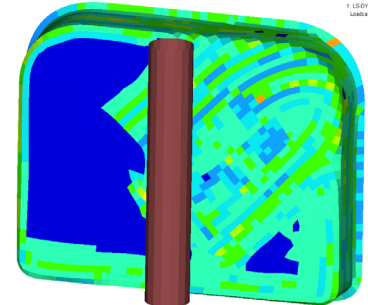- With the pathway established, this process will be scaled to all composite parts.

Without manufacturing residual stresses

With manufacturing residual stresses

Accomplishments - Cost Modeling

Developing parametric cost modeling

- With the door design frozen, a parametric cost model is currently being developed to account for variability in input costs and manufacturing process parameters.

Assumptions

1. Production volume per year is assumed to be around 20,000
2. Total number of direct and indirect workers for each machine are assumed to be 4
3. Rate of overhead (18~24% of total cost) is assumed by experience
4. Cost of carry over parts (~$180) is assumed to be constant
5. Cost of raw martials for carbon fiber nylon composites range from $31 to $46, depending on the type of reinforcement.

| Identifying parameters and developing cost estimating relationships	→	Parameterization of door design	→	Compute total cost with sensitivity analysis

- Electricity cost per kWh
- Scrap rate
- Mold life
- Equipment life
- Labor wage
- Production volume per year
- Overhead rate
- Material cost

Accomplishments - Cost Modeling

- A parametric function was developed to determine the final cost of the door assembly.
- The variability of each input parameter is fitted to a standard distribution.

Normal Distribution Plot
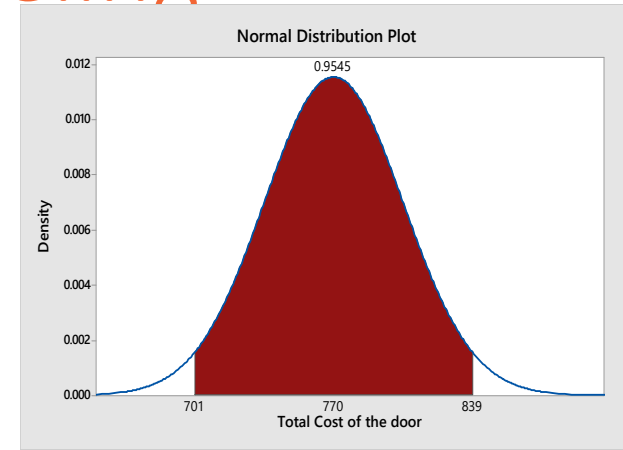
S.no	Parameter	Distribution Type	Mean ± 2SD	Distribution of total cost($)	Range of Total cost ($)	Probability
1	Electricity cost (cent/kWh)	Loglogistic	7.5~15	Lognormal	767~770	0.94
2	Scrap rate (%)	Lognormal	4~13	Largest extreme value	767~795	0.96
3	Mold life (yr)	Loglogistic	3.5~12.5	Logistic	723~820	0.96
4	Equipment life (yr)	Lognormal	5~13	Normal	760~775	0.96
5	Labor wage ($/hr)	Weibull	15~23	Weibull	744~772	0.95
6	Production per year	Weibull	14500~26500	Lognormal	723~830	0.96
7	Overhead rate (%)	Normal	15~27	Normal	754~801	0.95
8	Material cost ($/kg)	Weibull	31~46	Loglogistic	720~825	0.95

Identified parameters	Identified Variations	Total Cost($)
Electricity cost per kWh (cents)	7.5~17	**Mean**: $770
Scrap rate (%)	4~15	
Mold life (years)	6~11	**STD**: $34.5
Equipment life (years)	5~13	
labor hourly wage ($)	15~28	**Range**: $701 to $839
Material cost per kg (S)	36~46	

Assumptions made:
- Produced per year = 20,000
- Overhead rate considered = 20%

Response to Reviewer Comments

Comment from 2018 Annual Merit Review	Responses
"The reviewer said that the project is generally on track. There are several technical barriers particularly in that the weight optimization is done on a structural parts level while the overall weight is impacted by the system level. **Several traditional components are going to be used in the weight optimized composite structure. The reviewer recommended that an overall weight scenario including all sub-components** (existing and new) should be accounted for."	The team, is currently lightweighting other components of the door, such as rear view mirror, wire harness and weather sealing. In fact, an entirely new rearview mirror assembly was developed with aggressive part consolidation and up to 30% mass reduction
"The reviewer referenced prior comments and **suggested developing an understanding to capture the crashworthiness expected with the redesigned features and their interactions with respect to the traditional components such as window modules, etc.** The reviewer inquired if by excessive lightweighting, these interactions will adversely influence impact performance."	In the current set of simulations, all door internal components such as window regulation, latch assembly, window, etc. were included in these simulations. In fact, the interaction between the window regulator and inner panel caused some premature failures. In the current design this was avoided by slight repositioning the window regulator without affecting the function

Remaining Challenges & Barriers

- Reducing structural mass by 1.04 Kg.
  - Currently the door is ~1 kg heavier than the target. Additional mass can be removed from the door frame by optimizing the composite ply layup, as the door outperforms the baseline door in few test modes

- Cost modeling
  - Getting accurate raw material cost is challenging
  - Due to lack of historic data on capital costs for our proposed process, a detailed virtual plant model has to be developed

- Tooling lead time
  - The tooling lead time for inner panel tool is approximately five months. This is the critical path for manufacturing

Collaborations

Key Organizations	Role	Responsibilities
CLEMSON UNIVERSITY	Principal investigator	• Project management • Design development • Manufacturing/tooling design & simulation • Linear & NVH analysis • Cost & factory modeling • Discontinuous fiber material characterization • Non-Linear analysis
UNIVERSITY OF DELAWARE	Co - PI	• Non-Linear analysis • Continuous fiber 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
CORNING	Supplier	• Lightweight glazing design & prototyping

Suppliers, software and general participants

BOND LAMINATES — A company of the LANXESS group | BASF We create chemistry | Barrday ADVANCED MATERIAL SOLUTIONS | Altair | LSTC Livermore Software Technology Corp. | MSC Software | Moldex3D MOLDING INNOVATION | SIEMENS

Core Participant Profiles

Institution	Advisor	Personal	Standing
Clemson University	Srikanth Pilla (PI)	Veera Aditya Yerra	PhD students
		Sai Aditya Pradeep	
	Gang li (Co-PI)	Anmol Kothari	
		Madhura Limaye	
		Gaurav Dalal	Master's Student
	Srikanth Pilla	Senthil Ramesh	Master's Student
University of Delaware	Shridhar Yarlagadda (Co-PI)	Bazle Haque	Research Faculty
		Lukas Fuessel	Visiting scholar
Honda The Power of Dreams	OEM Partner	Skye Malcolm	Principal Engineer
	OEM Partner	Duane Detwiler	Chief Engineer

No. of students worked/working on this project: 7

Proposed Future Work

Three major tasks for financial year 2019 are:

1. Sub component testing : A hat section with a bonded spine, with same material systems and structural adhesive as the thermoplastics door is tested to validate simulation correlation.

2. Tool manufacturing : The aluminum thermoforming tools will be released to an external supplier at the end of Q2 2019 for manufacturing. The expected delivery for these tools is Q4 2019.

3. Prototype manufacturing : Prototyping will be carried out at Clemson Composites Center's thermoforming line in Q1 2020

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

Summary

Major goals accomplished in year 3

- The composite door meets all crash and static requirements.
- The door frame design is frozen.
- Manufacturing response pathway is established.
- Tooling is ready to be implemented.

Key takeaways

- Thermoplastic composites door frame can successfully meet the crash requirements.
- Steel anti-intrusion is lighter and economical than the composites anti – intrusion beam.