A SYSTEMS APPROACH TO DEVELOP ULTRA LIGHTWEIGHT COMPOSITE DOOR USING FIBER REINFORCED THERMOPLASTICS

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Abstract

Transportation is a significant contributor to environmental pollution, specifically from the emission of pollutants such as carbon dioxide, nitrous oxides and particulate pollutants. Consequently, research has been undertaken to develop alternative electrical vehicle technologies that are more efficient. While several approaches have been used to improve efficiency, the lightweighting of automobile components has proven broadly effective. While most research and studies focus on lightweighting the Body-in-White which contributes ~ 35% of total weight of the vehicle they often overlook/ignore closure systems. Closure systems are extremely important as they account for ~ 50 % of the structure mass and have a very diverse range of requirements including crash safety, durability, strength, fit, finish, NVH, and weather sealing.

The goal of this study is to design and develop a closure system which is 42.5% lighter than the baseline system, while ensuring the functional requirements at a moderate cost increment of less than $5 for every pound of weight saved. Such stringent requirements mandate a revolutionary yet holistic approach to product design rather than a simple materials substitution or design optimization. Hence, here we employ a systems approach to redesign an existing steel door using composites-enabled technology. Considering the design freedom and manufacturing benefits of composites, our systems approach enabled consolidation of 40% of the parts of the door compared to baseline assembly while still meeting the functional requirements. The enabled technologies as part of our design and development process include: high-performance continuous and discontinuous fiber reinforced thermoplastics resin systems, 'Manufacturing-in-loop' simulation methodology, parametric cost-modeling, near-geometry and production-scale manufacturability. The study will provide an overview scope with up-to-date progress on our material data development, design evolution, systems approach, simulation methodology and results.

Introduction

Vehicle lightweighting provides opportunities for enhancing fuel efficiency. Often it is the vehicle body (aka body-in-white, BiW), the heaviest structure of a vehicle, that is the key target for new weight reduction strategies within the vehicle architecture. Within the body, closures contribute

35-50 % of the mass and are very challenging to lightweight [1]. A technology (designs, materials, and process-methods) that is developed for closures is hypothesized to seam into the BiW without major technical barriers. Moreover, closures are often produced as stand-alone subsystems and assembled late in manufacturing. As such, their innovation would lessen the technological constraints related to vehicle assembly. It is in this regard that the Department of Energy's (DOE) Vehicle Technology Office has set a challenge to lightweight a fully assembled driver's side front door by at least 42.5 % but not spending more than $5 for every pound saved. This presents a complex challenge as the mere implementation of approaches such as design optimization and material substitution will not achieve 42.5% lightweighting.

A baseline door with a traditional steel frame behind the glass architecture was selected from a 2014 model year mid-size luxury crossover for the North American market. The requirements mandate that the Ultra lightweight composite door (ULWC) door have a good sealing with the existing body in white (BiW) structure and meet all the requirements of the baseline door with a manufacturing process that is scalable to 20,000 units per year. The scalability requirements eliminate most of the traditional manufacturing processes like resin transfer molding and autoclave and materials such as fiber reinforced thermosets. With the recent advancements in manufacturing thermoplastics composites with fast cycle times [2], the door frame was developed entirely from fiber reinforced thermoplastic.

An extensive part consolidation exercise was performed to help achieve the 42.5% weight reduction, which reduced the part count by approximately 45%. The design freedom offered by the materials and manufacturing processes was a primary motivation of this reduction. A combination of materials, specifically uni-directional tape, discontinuous mats and injection molded long fiber pellets were used in the door frame. In addition to the mass reduction to the frame, other components of the door sub systems such as glazing, rear view mirror and trim panels were also subjected to redesign to achieve the weight reduction target. This paper gives a detailed overview of the lightweighting process and concept design for the ULWC door.

Baseline Door Analysis

A baseline steel driver side door from a mid-size luxury crossover was selected for the ULWC door replacement. This baseline steel door represents the state-of-the-art in terms of lightweighting and performance for conventional steel frame behind the glass architecture. A teardown benchmarking study was performed on the steel door to determine the weight of each component, get a better understanding of the design, manufacturing and assembly, during which a fully assembled door was disassembled to the last nut and bolt. Each of these components were then weighed to create a detailed bill of materials.

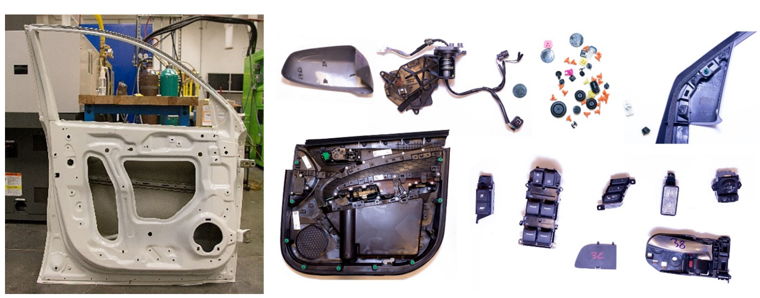

Figure 1 Steel doorframe with hinges and components from the OEM door.

The door comprises 54 parts (excluding the fasteners) that are classified as either rigid polymers, metals or elastomers as shown in Figure 2. The door frame is the heaviest component of the entire door assembly, approximately contributing close to 49% of the total mass, while the trim, electronics and windows contribute to another 31% as shown in the Figure 3.

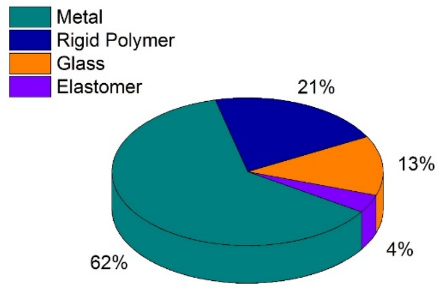

Figure 2 Weight distribution by material groups in the baseline door.

Metals constitute a majority of the total mass (~ 62%) wherein the door frame consists of regular cold drawn steel and high strength steel are used in the door frame.

Figure 3 Weights of major subassembly of the baseline door.

Design Requirements

As part of the solicitation from Department of Energy's Vehicle Technology Office, the ULWC door must meet or surpass the baseline metal door in terms of mechanical performance, crash safety, fit, finish and durability while ensuring an expenditure of only five dollars extra for every pound saved from the baseline door.

The design requirements for the ULWC door are as follows:

1. Mechanical requirements

    a. Static load cases: These load cases represent the daily use and misuse of the door frame over its life span. Six individual load cases were provided by our OEM partner: (1) door sag closed (DSc); (2) door sag open (DSo); (3) door strong open; (4) beltline stiffness; (5) sash stiffness near latch; and (6) sash stiffness near hinge.

    b. Nonlinear load cases: These load cases represent crash tests affecting the door frame from the National Highway Traffic Safety Administration (NHTSA) [3] and the Insurance Institute for Highway Safety (IIHS) [4]. A total of five crash tests were picked for evaluating the ULWC door frame as shown in Figure 4.

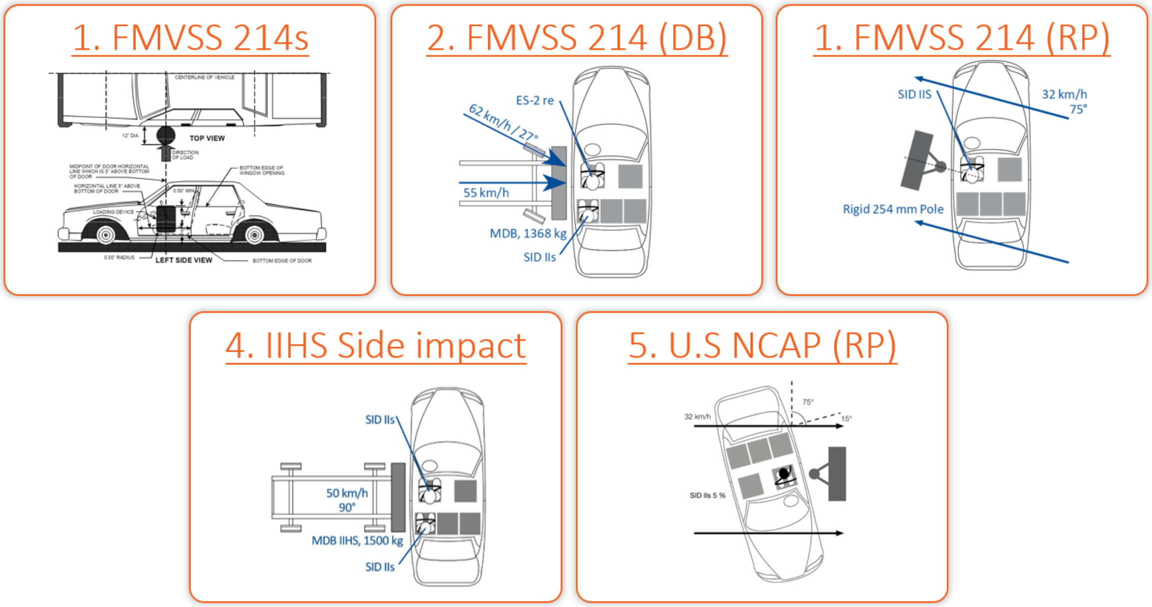

Figure 4 Non-linear load cases.

2. Sealing requirements

One of the key requirements of this project entailed developing a door to interface with existing BiW, the Base line door has two weather strips and two wind deflectors, and the ULWC door will use the same weather strips and sealing surfaces to maintain a good seal with the existing BiW.

3. Noise, vibration and harshness requirements (NVH).

The door frame acts as a critical route for transmitting vibration, structural bound and air bound noise into the passenger cabin. Statistical energy analysis tools were used to determine the ULWC door performance.

Concept Development

An iterative process was used in developing and evaluating conceptual designs for the ULWC door. This process was divided into four phases, for each subsequent phase the conceptual designs evolved towards the final design requirements. From the very beginning of this process, it was clear that the design optimization or material substitution would not yield a design concept that meets the mass reduction requirements. Therefore, it was important to understand the requirements from a systems level to develop a door frame that would meet these requirements with the least number of parts. This six-phase concept development is detailed in Figure 5. In Phase 1, rough computer aided design (CAD) models were developed to test our hypotheses that the commercially available fiber reinforced thermoplastics can meet the project. In Phase 2, these designs were further refined to fit within the design envelope of the baseline door frame, during which the design space for the certain structural members were found much smaller than previously anticipated. The packaging restrictions created by the other door components (i.e. window regulator, window glass, weather sealing and other mechanical components) were the cause of this smaller space. Using the data from Phase 2, seven unique door concepts were developed during Phase 3 with three of these down-selected for further detailing. Additionally Phase 3 entailed a deeper understanding and analyzes the current door geometry and sealing planes. The three down selected concepts were further detailed in Phase 4, and finite element analysis was used to select the two most promising concepts for further development.

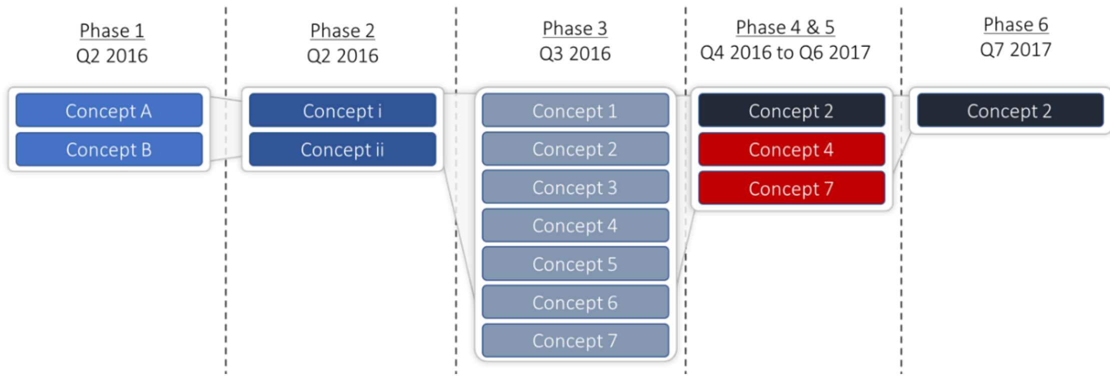

Figure 5 Concept development history.

The entire structural part of the door frame as a single component encompassed Concept 2. Although the manufacturing was quite complex, the quality, ease of assembly, and time required for the door assembly were all vastly improved. The other advantages of this design were very tight tolerances derived from the manufacturing of the doorframe from a single mold, and very few lazy parts, making the lightweighting potential for this door concept quite high. The door trim and the door module were integrated into the door frame, as shown in Figure 6.

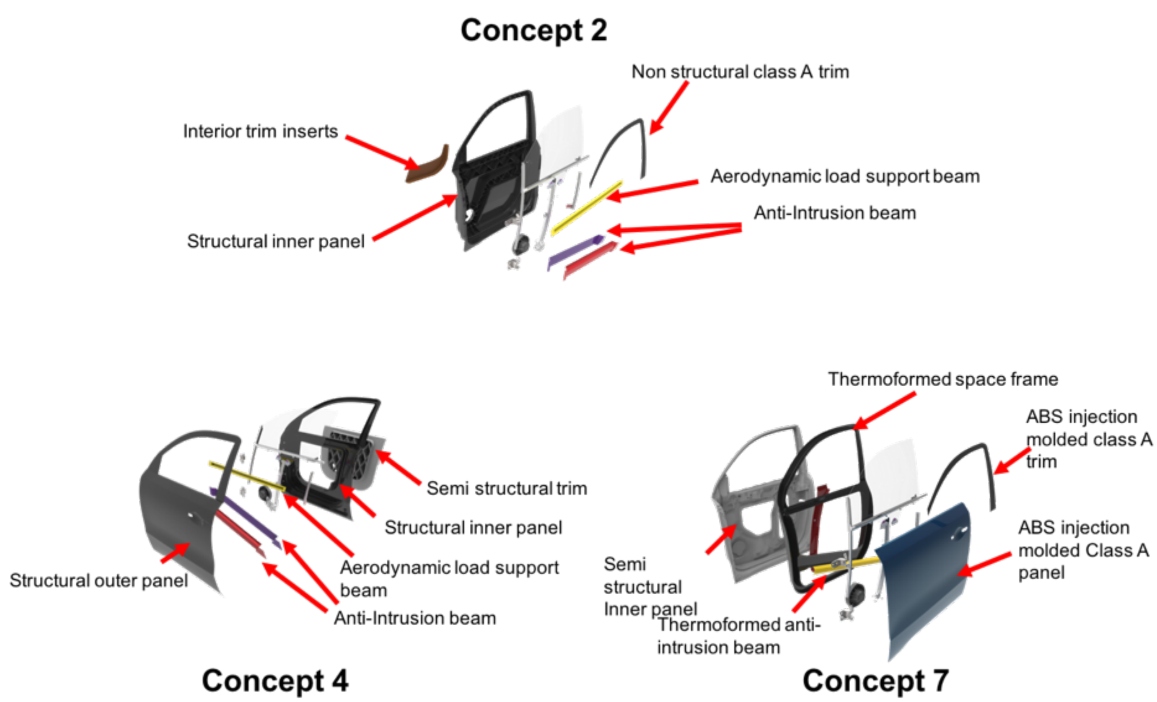

Figure 6 Concepts 2, 4, and 7 exploded view.

Concept 4 is a two-piece structural design consisting of the door frame manufactured from a two-shell structure, which was later bonded to form the door frame−very similar to the baseline steel door design. The advantage of this concept was its relative simplicity for manufacturing in that both the inner and outer panels could be thermoformed from endless fiber thermoplastics tapes, while the interior trim constituted a semi-structural member. The semi-structural trim attached to the frame provided an additional in-plane stiffness to the inner panels, thus contributing to overall door frame stiffness. This trim could be manufactured from injection-molded long/short fiber reinforced thermoplastics. Unfortunately, the drawbacks of high number of lazy parts, high estimated cost, and low lightweight potential made Concept 4 unworkable. Concept 7 is a space frame-inspired design where the major structural loads are carried by a space frame structure that consists of an open hat section around the periphery of the door frame as shown in Figure 6. The key load points of the hinges and latch, were directly attached to the space frame. A semi-structural inner panel was mechanically fastened to this frame, while a removable class A panel on the vehicles' exterior served as the access point to the doors interior.

From Phase 4 onwards, the team focused on the detailing of Concept 2 and 7 to satisfy all geometry requirements (e.g., sealing planes), which were interfaced with all sub-assemblies/door internal components. Concept 2, as shown in Figure 7, incorporated an injection molded ribbed structure made of Long Fiber Thermoplastics (LFT) on the inner panel that acted as the main load bearing structure of the door frame with anti-intrusion beams to prevent intrusion during side impact. The full geometrical integration of door sub-assemblies (i.e., window regulator, latch/hinges hardware, electronics, and door stopper) to the inner panel is also shown in Figure 7. The attachment of components with negative drafts and complex details, such as the hand rest and door pocket, via snap fit to the frame were the key advantages of this iteration of Concept 2. This panel could be later covered with foam laminated leather or fabric for a premium feel. After all internal components were attached, a removable class A panel was mechanically attached to the door assembly. The high functional integration of the inner panel and minimization of distortion during the thermoforming process were the primary challenges associated with this concept. Minimizing the complex geometry, such as the compound curves surface and aggressive bend radius, was the primary method for resolving such problems.

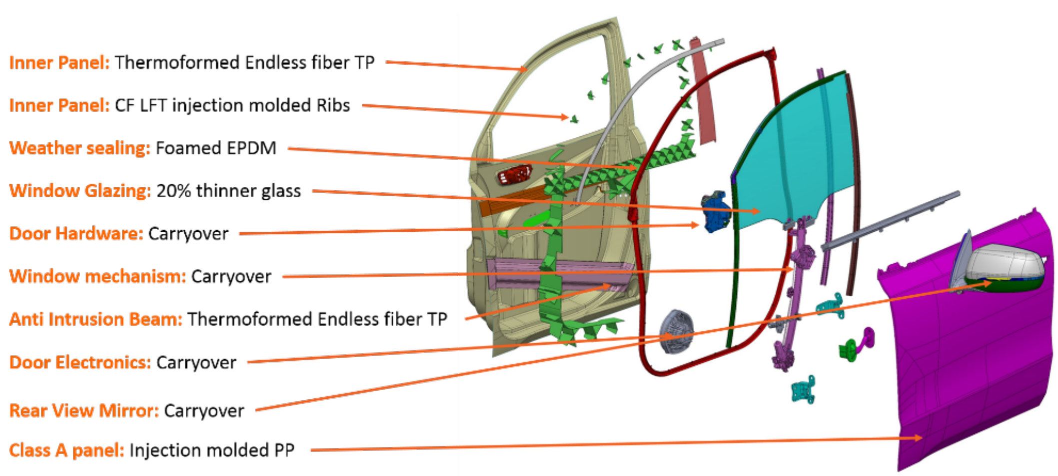

Figure 7 Concept 2 exploded view (TP = thermoplastic, CF = carbon fiber, EPDM = ethylene propylene diene monomer, PP = polypropylene).

A detailed CAD of Concept 7 with the window hardware (including window, guide rails, and hardware), non-structural trim, door limiter, and hinge/latch hardware was developed as shown in Figure 8. The key features are an injection-molded nonstructural inner trim and outer panel, with the same method used to snap-fit the space frame and the inner trim geometry identical to that in Concept 2. The outer panel can be snapped into both the space frame and the inner panel to ensure the maximum access area for assembly. The complex curvature of the inner panel presented challenges during thermoforming, while the intrusion beam position also posed concerns in terms of both impact and crash performance.

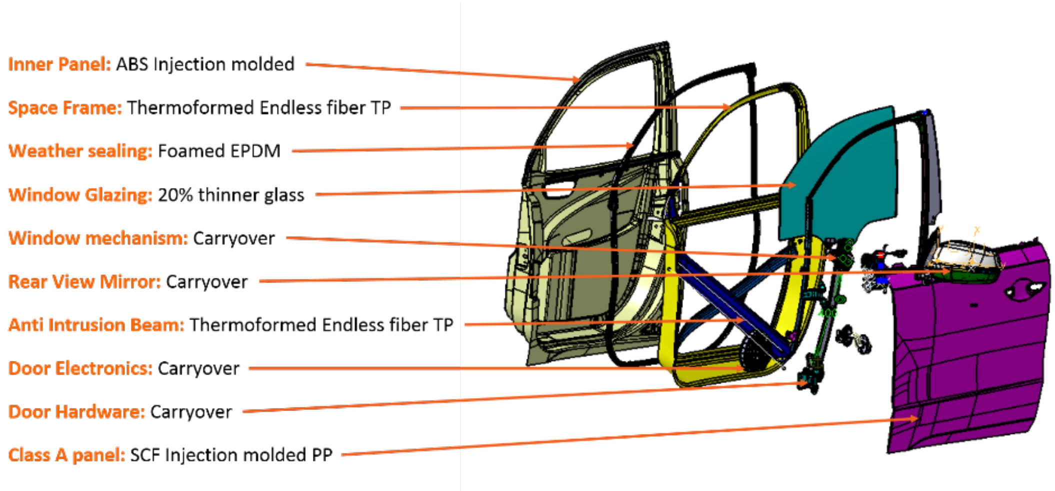

Figure 8 Concept 7 exploded view (ABS = Acrylonitrile butadiene styrene, TP = thermoplastic, EPDM = ethylene propylene diene monomer, SCF = supercritical fluid; PP = polypropylene).

Phase 5 entailed optimizing the mass of Concept 2 by exploring different reinforcing geometries for the inner frame in addition to optimization. The detailing of the door design to interface with all sub-assemblies was also a priority. The addition of this reinforcement member (shown in green in Figure 9), mounting interfaces for the rear-view mirror, window regulator, and interior door release was completed without any additional brackets or secondary structures, thus preventing lazy parts. This new member (shown in green in Figure 9) also serves as a local reinforcement for multiple point loads, thus enhancing the performance in the rear-view mirror mount & window regulator stiffness, and mitigating door sag by reinforcing the upper hinge that forms a load path between the two.

As these geometric changes in the structural frame were finalized, composite-ply optimization was conducted to further minimize the mass. Geometry optimization and parametric studies were also conducted to minimize the weight of Concept 7, while meeting the static requirements. Door sag was chosen as the primary requirement for parametric studies with several parameters and geometric variations on the concept evaluated. These results were used to further refine Concept 7, which is shown in Figure 9.

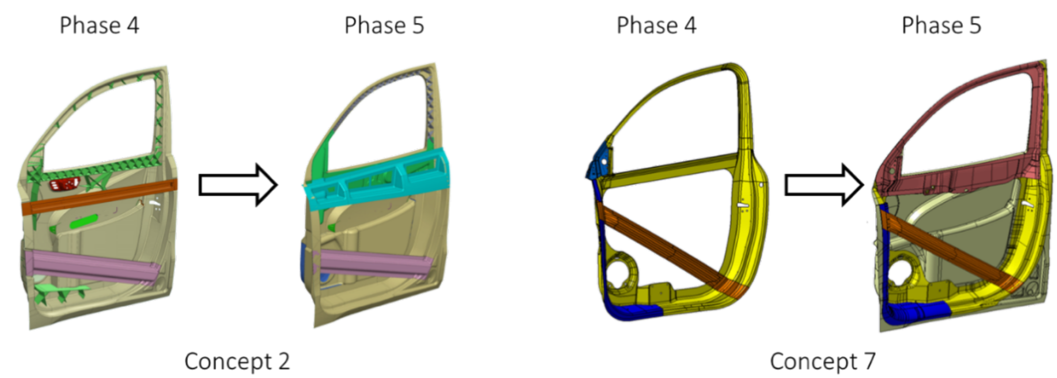

Figure 9 Design update to Concept 2 and Concept 7.

In Phase 6, the team carefully evaluated both designs and determined a multiple convergence of both concepts to the same fundamental load-bearing design. As such Concept 2 assumed priority as the main exemplar going forward, to which the key findings from Concept 7 were added. This unified design, shown in Figure 10, included a revised inner panel design, a modified outer beltline support beam, and the integration of both the class A panel and the interior trim development. The inner panel was redesigned to accommodate several mounting features and simplified geometry for easier manufacturing. The outer beltline support beam was designed to interface with the door handle mechanism. The class A panel was modified with a combination of snap fits and mechanical fasteners for ease of attachment. Lastly, since this concept had no interior trim panel, discussions were held with our OEM partner to discern an acceptable surface quality that the customer could see and feel.

Figure 10 Final selected design – Concept 2 (UD = unidirectional, LTF = long fiber thermoplastic, SFT = short fiber thermoplastic).

Performance Analysis.

Early in the concept development phase, the team identified critical zones with in the door frame that contribute to overall stiffness as shown in Figure 11. This knowledge then informed the appropriately design and sizing of different zones with in the door frame for optimal performance. The most critical area is the hinge side of the door frame, a zone that is crucial in transmitting load from the door to the BiW. Ply boundaries were created using these zone shapes for optimization and Altair Optistruct was used to determine the optimal laminates for the static load cases. The objective of the optimization is to minimize mass, while meeting all stiffness requirements to satisfy static load cases. A third optimization for static load cases was performed on all three concepts which were developed during Phase 4. Again, Concept 2 was found the lightest of all three doors.

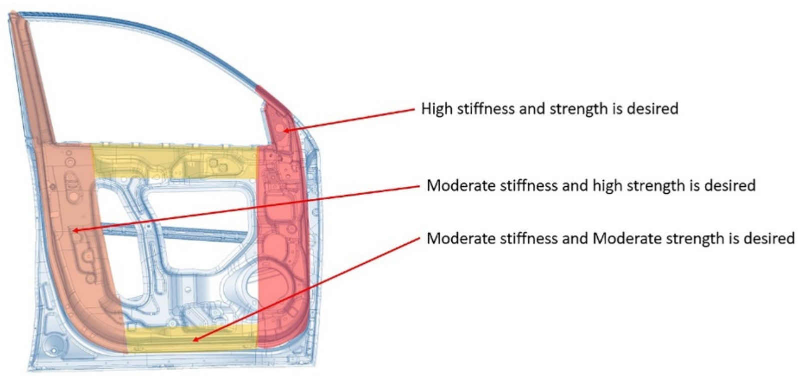

Figure 11 Strength and stiffness zones on the door.

A three-step optimization process, which involves free-size, size and shuffle optimization steps, was then established. The total thickness of each of the finite elements in a component is reduced from its initial value to a feasible value satisfying the load cases and manufacturing constraints. In the second step, size optimization is performed to assign discrete values to each ply in the component. In the final step, shuffle optimization is used to optimize the stacking sequence of the plies in laminates.

In this free-size optimization, all components except anti-intrusion beam and support beam were included in the objective function for mass reduction. The exclusion of these two beams from the optimization for static load cases provide a redundant initial design. Both were optimized for the quasi-static load case and crash test since they are the primary load bearing structures in these cases.

For free-size optimization, two types of constraints were applied:

I. Displacement constraints,

II. Thickness constraints.

The displacement constraints are that which the load cases require. The thickness constraints, however, consider manufacturable thickness of a certain component depending on the manufacturing process or material used. The minimum required thickness for a composite component was 1.2 mm and 1.0 mm for non-composite shells, which were the outer panel and ribs in Concept 2). This minimum thickness of 1.2 mm was considered, which was informed by other performance criteria such as NVH and manufacturability as shown in Figure 12.

Optimization problem:

Minimize total mass (objective function):

$M_1+M_2+\ldots+M_i$ (i: door component number)

Subject to (constraints):

$$DS < \begin{cases} 6 \text{ mm for near closed position} \\ 5 \text{ mm for fully open position} \end{cases}$$

Sash A < 3.5 mm

Sash B < 4.0 mm

$T_{initial} > T_i > T_{man}$ where T: total thickness of component i

$T_{initial}$: initial thickness

T_{man}: min. manufacturable thickness

Ply thickness = 0, 0.15 mm, or 0.3 mm (for size-optimization)

Figure 12 Optimization problem.

Table 1 Optimization results of the three door concepts in phase 4.

		Concept 2		Concept 4		Concept 7
Door Sag Load Case		Nearly Closed	Fully Open	Nearly Closed	Fully Open	Nearly Closed
Mass Optimized Components		Inner Panel, Outer Panel, Ribs		Frame, Outer Panel		Frame
Optimized response vs. requirement (mm)	**DS**	5.98<Req	4.98<Req	5.99<Req	4.99<Req	4.28<Req
	SR_A	3.49<Req	3.49Req	3.12<Req	3.12<Req	2.9<Req
	SR_B	2.51<Req	2.52<Req	3.06<Req	3.06<Req	1.6<Req
Optimized mass (kg)		5.31		5.21		7.62
Target mass (kg)		9.42		6.18		6.18
Baseline weights (kg)		18.21 (frame + trim panel)		15.01 (frame only)		15.01 (frame only)
Lightweighting percentage		71%		65%		49%

The optimization results of Concept 2 indicated a similarity of the thickness distribution of the inner panel for both cases with a greater thickness around the hinge bolts and at the intersection of the window frame with the door (red regions of Figure 13. The thickness of the lower part of the inner panel was reduced to the minimum allowable value in all cases, indicating the possibility of further reducing mass if thinner laminates can be manufactured. Moreover, the thicknesses of the outer panel, part of the inner panel, and the ribs without a window frame were reduced to the minimum allowable value. As such, our findings created other possibilities for further weight reduction, such as in the partial removal of ribs.

The optimized mass was 5.31 kg (65.6% mass reduction) for the nearly closed-door position and 5.21 kg (66.2% mass reduction) for a fully open door, which was below the target value of 9.42 kg (only structural mass). Note that this value includes 3.24 kg trim mass, since this concept had a built-in trim design. The optimization results for Concept 4 shows a reduction of the whole frame and outer panel thicknesses to the minimum allowable value of 1.2 mm, except for the thickness around the hinge bolts. These findings clearly indicated the possibility of excess material in these components if thinner laminates could be manufactured. The optimized mass of Concept 2 is 5.31 kg, whereas it was 5.21 kg and 6.18 kg for Concept 4 and Concept 7 respectively. However, Concept 2 includes trim panel unlike Concept 4 and Concept 7, thus the target mass for concept 2 and concept 4 & 7 are different. Due to this difference in target mass, lightweighting percentage (with respect to steel baseline door) was used as the primary factor in down selecting these concepts. Concept 2 achieved best lightweighting percentage when compared to concept 4 & 7 as shown in the Table 1.

In Phase 6, Concept 2 was further refined with an inner belt line support and outer beltline support for purposes of replacing the previously used injection molded ribs to increase local stiffness. The mass of the door after size optimization was determined as 7.19 kg when the minimum allowable thickness was 1.2 mm. The thickness distribution of the inner panel in Figure 13 shows that the panel is thicker (3.6 mm) around the part on which the mirror is mounted, and at the edges on the frame where the speaker is mounted, shown by the red regions in Figure 13. The thickness in the other regions of the inner panel is reduced to 1.2 mm, which is the minimum manufacturing constraint. Shuffle optimization was then performed on the modified Concept 2. The thickness of plies was redefined based on the thickness distribution results after size optimization with two distinct minimum manufacturing constraints used (i.e., 0.15 mm and 0.3 mm). The final stacking sequence obtained for the inner panel and the beltline support is shown in Figure 14. This modified version of Concept 2 was found to satisfy all static requirements.

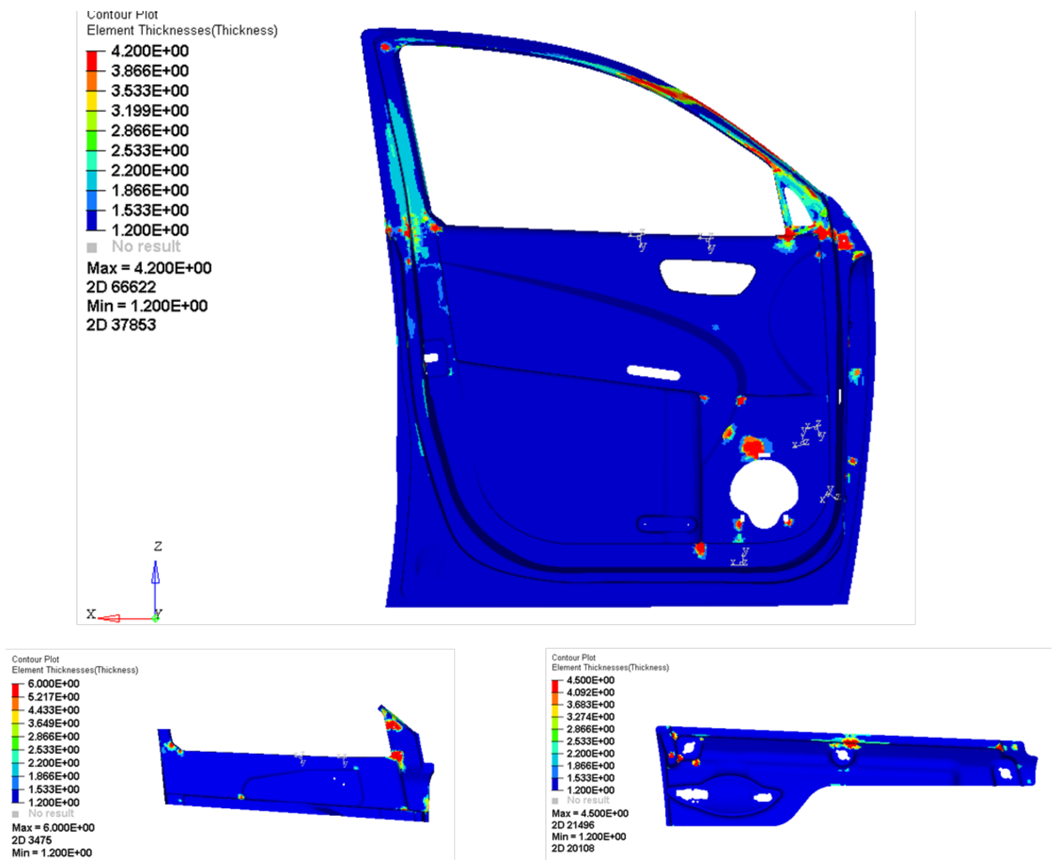

Figure 13 Thickness distribution for inner panel, inner beltline member and outer beltline member after size optimization

Iteration 0	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5
19	22	25	25	25	25
20	21	21	21	21	21
21	19	23	23	23	23
22	20	19	19	19	19
23	26	22	22	22	22
24	25	26	26	26	26
25	23	20	20	20	20
26	24	24	24	24	24

Legend
90.0 degrees
45.0 degrees
0.0 degrees
-45.0 degrees

Figure 14 stacking sequence after shuffle optimization for inner panel.

Non-Linear Load Cases

Energy absorption capacity is critical for ensuring that the door frame meets the federal and OEM specified crash requirements. Metal structures generally exhibit slow progressive failures, which is desirable for maximizing energy absorption [5]. Most carbon fiber composites have a morphology that is characteristically brittle, thus resulting in abrupt fractures and very little energy absorption capacity. The use of a thermoplastics matrix instead of thermosets can mitigate this failure. While this effect is very desirable for crash test, it is also accompanied by a reduction in stiffness, thus requiring a careful design of the laminates to utilize the best of both effects. A 45°/-45° laminate was used for the anti-intrusion beam to delay the fracture and increase beam bending. It was necessary to add reinforcement plies to the door frame to prevent premature fracture in certain areas, which increased the overall weight. FMVSS 214 static [6] was selected as a preliminary analysis to verify crash performance, for use only on the door frame outside the vehicle body, thus improving the trace failures to root causes and make changes respectively. After the door met the requirements of FMVSS 214 static, the remaining test simulations were performed.

Several materials and ply lay-up analysis were performed to elucidate the deformation and failure modes of the door and door sub-components during the applied load case. Therefore, simulations with two different materials and two-ply sequences were conducted to resolve the hinge loading difficulties and elucidate the failure modes of a composite door under this type of loading. Two material systems - AS4/PEI and AS4/NYLON which were used in both the static optimization and nonlinear load simulations. . The first composite is a symmetric Quasi-Isotropic $[0/45/-45/90/0/45/-45/90]_s$ layup and the second is a symmetric ± 45 layup, which provides the maximum degree of strain in the composite [7]. Both are 16 ply and both have a total thickness of 3mm.

The force displacement plots for the initial set of simulations is shown in Figure 15. The LS-Dyna predictions show that all simulations meet the requirements of the FMVSS 214 static test in the first 2 Stages. The LS-Dyna animation of material and door deformation show progressive damage in all cases, and the failure modes follow a similar pattern in all cases. The crushing of the hat section of the anti-intrusion beam was the causative factor behind the first reduction in force between 40 mm to 80 mm of displacment). The PEI and the Nylon quasi-isotropic laminates indicate another reduction between 130 mm to 165 mm. In these cases the intrusion beam fails under the pole impactor. The next visible failure in all models occurs when the impact beam makes contact with the inner trim, which fails at the window regulator location. The local change in geometry (bottle holder in inner trim) is the cause of this accrual of the local stress in this region.

In all simulations, the hinge and latch location was determined a critical location point of failure, thus requiring the addition of composite layers to distribute the forces around the hinge areas. An assessment of deformation mechanisms determined an overt rigidity of the adhesive bonded regions, unlike the material which was significantly more compliant. Therefore adhesion studies were conducted to determine a more accurate response and identify the appropriate adhesive modeling technique. Future runs will entail the use of the cohesive elment formulation to model all bondlines. The team has already begun simulations with a modified geometry, cohesive element adhesive formulation and additional door configurations to evaluate failure modes and deformation mechanisms.

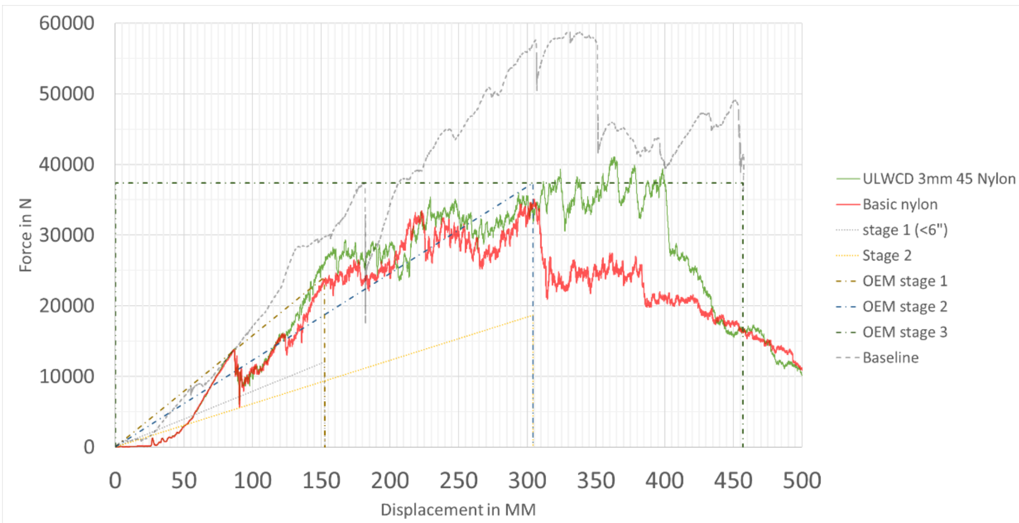

Figure 15 Force-Displacement plots for ULWC door with Different Laminates.

The addition of metal plates in both the window regulator and in the outer-panel-stiffener are also viable options for improving performance as shown in Figure 16. Indeed, the simulation of these plates significantly improved the performance in the second and third stage due to the plastic deformation capacity for the metal plates. Unfortunately, despite the benefits the added weight from these plates precludes their use in a sustainable light weight design.

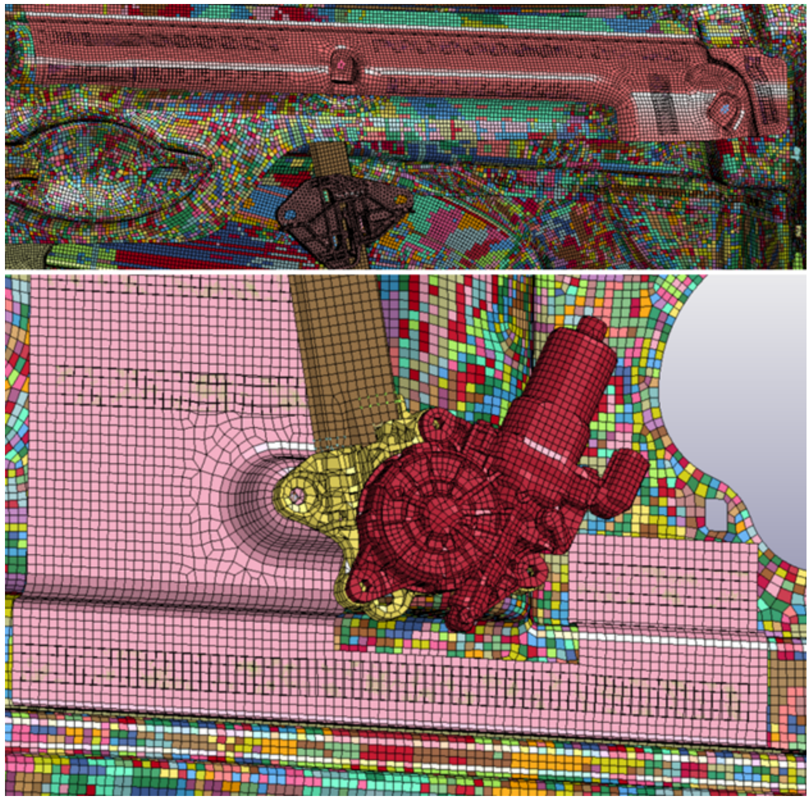

Figure 16 Metal reinforcements.

Future Work

The use of discontinuous fiber reinforcements and off axis plies are most promising for increasing the energy absorption capacity without any additional mass. The effect of using such reinforcements on both static and non-linear performance is now currently under evaluation. Once the design meets the FMVSS 214 static test while meeting the weight and cost target, the remaining four crash tests will be conducted to validate the ULWC door design. In a parallel manufacturing simulation, both thermoforming and injection molding will be undertaken to understand the effect of process variables on mechanical performance. The expectation is a freeze and subsequent prototyping of the design by September 2018. The ultimate goal of this project is to subject the ULWC door to an entire battery of tests (i.e. full vehicle crash, durability, fit and finish) to determine if the initially defined targets were met.

Conclusion

Fiber reinforced thermoplastics offer a huge potential for lightweighting in the automotive industry. Thus far, the team has made excellent progress in developing a ULWC door manufacturing process using carbon fiber reinforced thermoplastics. The use of such thermoplastics will easily resolve the difficulties of mass production, cost and recycling. During this entire process the team identified certain limitations in current commercially available finite element analysis to simulate manufacturing of these materials system. Such efforts are critical providing badly needed data to determine the effects of manufacturing processes regarding the performance of the finished part. Determining the NVH performance of this door is also most critical informing the development of novel fiber reinforced thermoplastics parts in automotive applications.

Acknowledgements

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