II.2.3 Ultralight Hybrid Composite Door Design and Rapid Manufacture (TPI Composites Inc.)

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Project Introduction

New corporate average fuel economy regulations require improved fuel efficiency of the future vehicle fleet. Weight reduction is key to achieving these targets. Replacing metallic body and chassis components with carbon fiber-reinforced composites (CFRC) offers the most weight reduction potential at up to 70%. The introduction of the BMW i3 and i8 in 2014 required mass production processes to meet 20,000+ units per year. Preforming with High-Pressure Resin Transfer Molding (HP-RTM) has been implemented and meets rate, cost, and performance requirements. Our team members—Krauss-Maffei, Hexion, and Saertex®—were extensively involved in technology development (i.e., manufacturing, materials, and preforming) with BMW (only one of the manufacturers utilizing the technology) and brought this experience to our team, led by TPI, the vehicle original equipment manufacturer (OEM), and the University of Delaware Center for Composite Materials (UD-CCM). We will advance these technologies to develop an ultralight driver's side door for the vehicle with production rates of 80,000 units annually.

TPI has over 40 years of experience in the design, testing, prototyping, and production of lightweight composite structures and is leading the team of industry and academic partners with knowledge in all aspects of vehicle design and composite materials. The OEM will provide system requirements, integrate the ultralight door into the vehicle, and validate the design during vehicle testing. Krauss-Maffei, Hexion, Saertex, and Creative Foam will demonstrate their next-generation material and process solutions, while University of Delaware – Center of Composite Materials (UD-CCM) is world-renowned for their composite expertise in all aspects of composites R&D. The team will implement the new composite door design and evaluate integration and manufacturing challenges to meet automotive rate and cost targets.

Objectives

The objectives for this project are to address the following targets and technology gaps:

Target: Reduce part count and full-system weight by a minimum of 42.5%.

Gap: Current materials and methods utilize steel as the main structural component, adding mass to the overall structure, thereby reducing the vehicle fuel efficiency.

Target: Cost increase will not exceed $5 per pound of weight saved.

Gap: One of the major lightweighting materials at our disposal—CF—is upwards of $10–$15/lb. This material must be used judiciously to meet the cost targets.

Target: Materials and processes will be demonstrated to meet the production rate and performance requirements (an approximate four- to five-minute cycle time is required to meet annual production rate).

Gap: Standard composite manufacturing processes can process these parts at a cycle time of about one-hour per part. New injection technologies and resin formulations have opened the possibility of faster cycle times.

Approach

Development of a vehicle BIW is a very complex and time-consuming process because various, often-conflicting, functional requirements must be considered. Introducing new designs to reduce vehicle weight requires a systems approach where new designs can be quickly iterated and refined to evaluate their performance. This is particularly true when metals are replaced with composite materials because composite materials have significant potential to reduce weight when designs are fully optimized for parts consolidation and engineered properties using a variety of available material, fiber layups, and processing choices.

A typical automotive door is made from a combination of materials, including steel, plastic, and glazing. The structural materials are heavy, while the non-structural components do not contribute significantly to structural performance. Elements are joined together, increasing manufacturing and assembly cost and weight. We propose to replace all structural parts of the front side driver's door with continuous reinforced composites (with a weight-savings of up to 60%), reduce part count and system weight through part consolidation, and evaluate alternative glazing materials. This approach has the potential to meet and exceed the goals of 42.5% system weight reduction as compared to the steel door baseline and to meet cost targets of $5 per pound weight saved. The team will take a systems approach to meet the targets, as seen in the flow diagram in Figure II.2.3.1.

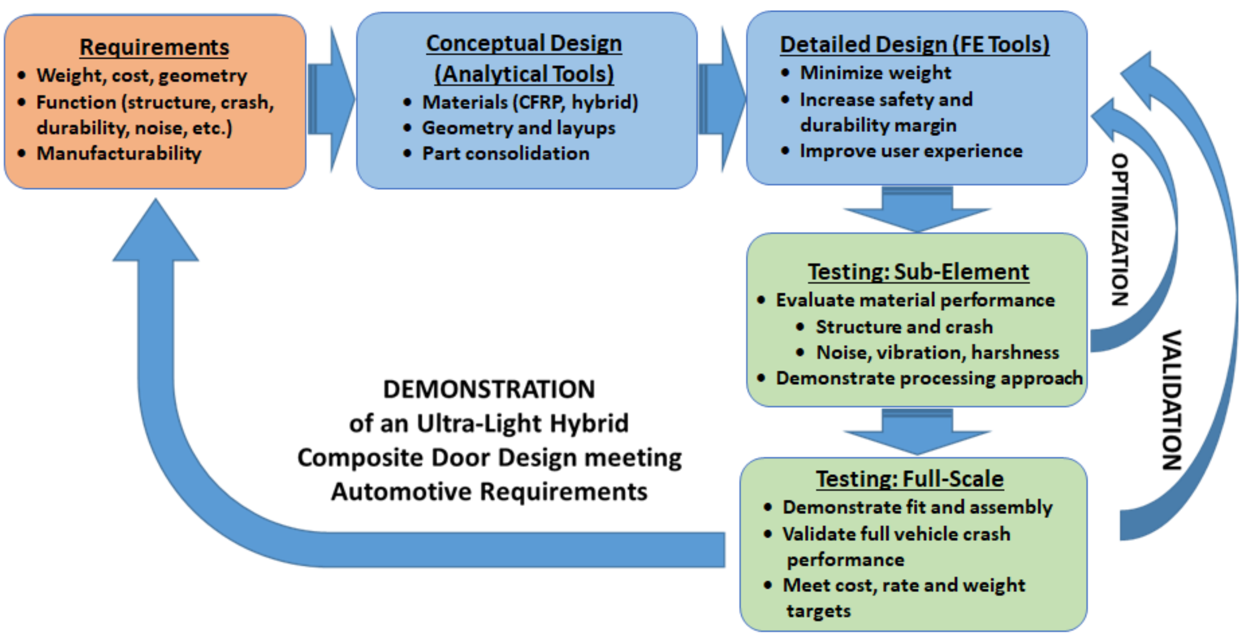


Figure II.2.3.1. Systems approach for reducing weight in complex automotive structures including the use of FE tools for detailed design. Source: University of Delaware.

This approach relies on the use of computational engineering analysis and simulation tools combined with sub-element testing to rapidly develop and evaluate design changes while full-scale testing is used to proof out the final design. The program will define the design requirements (such as weight and cost targets), functional and topology constraints, and consider the ability to manufacture the door at the required rate and performance. Cost; structural; crash; NVH; and manufacturing simulations exist and will be utilized. These individual simulation tools are state-of-the-art, commercially available, and have been validated on numerous occasions. Conceptual designs will be evaluated at the sub-element level to evaluate material performance (i.e., structure; crash; and NVH) and to demonstrate that the processing approach meets rate and quality targets. Full-scale test articles will be manufactured to validate form, fit, function, and cost of all integrated structural and non-structural components. A small number of design iterations may be required to optimize the various configurations.

The approach will allow (1) a shortened design cycle, resulting in reduced development time and costs; (2) elimination of trial-and-error process and part trials reducing tooling and manufacturing costs and (3) an optimum door configuration at minimum weight leading to a more cost-competitive product. The overall approach will be demonstrated on a composite door solution for the vehicle, but it is also applicable to a wide variety of automotive components. The comprehensive systems approach for designing, manufacturing, and validating a complex ultra-lightweight composite automotive component using a validated, multidisciplinary design tool with a small number of manufactured components for validation will reduce risk to convert metal structures to composites.

Predictive engineering tools guide material and design down-selection and are critical for eliminating trial-and-error and reducing cost and time. Figure II.2.3.2 shows the design environment the team will employ to evaluate the composite door structure.

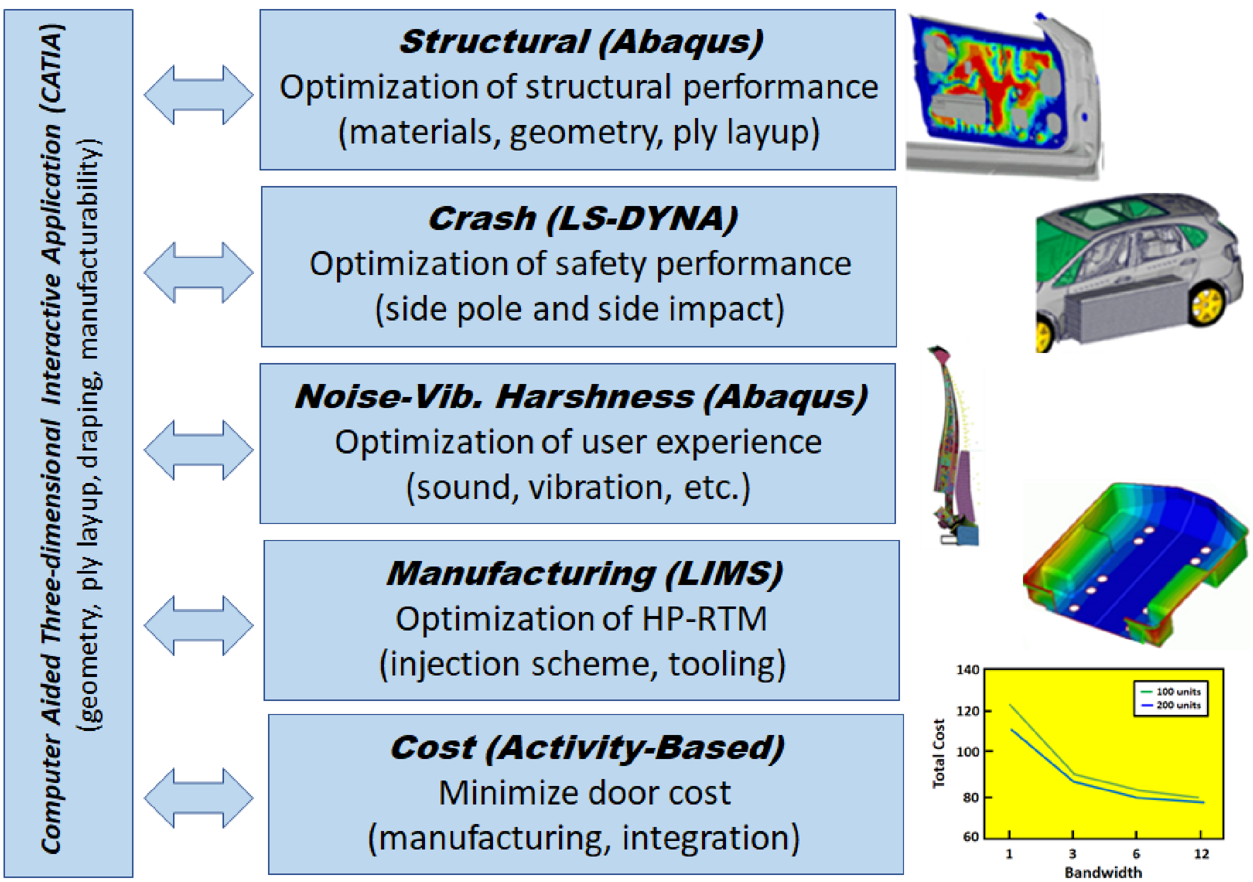


Figure II.2.3.2. Integrated predictive engineering environment. Source: University of Delaware.

Dassault System's computer-aided three-dimensional interactive application product design solution is our product development platform that easily communicates with other simulation tools. This enables multiple disciplines to share geometry, ply layup, and manufacturing-induced fiber orientations. Thus, designs are developed in one environment and then evaluated in the specialist applications across all phases of the product development process. For example, an important aspect of composite manufacturing is the effect of draping the fiber layer onto the mold surface, resulting in changes of the local fiber orientation. This can affect the infusion behavior during resin injection and the structural and crash performance of the final part. Our approach captures manufacturing-induced variations in the design and feeds these properties into all sub-models. Another example is potential sandwich constructions where the design not only improves structural stiffness, but also noise attenuation (improving ride experience) with novel foam solutions. Integration of other non-structural functional door items (e.g., speakers, glazing, and electronics) are captured in the design and are fed into the appropriate models and concepts.

The existing vehicle steel door is used as a baseline and the ability to reduce part count with a composite structure will be investigated. Part consolidation reduces weight and cost because a smaller number of parts must be manufactured. Assembly time and associated labor costs can be significantly reduced as well. The HP-RTM process allows complex geometry part fabrication, which enables integration of features into one component. Figure II.2.3.3 illustrates the potential part count reduction of a steel door with an equivalent composite structure [1]. Part count reduction alone will not be able to meet our weight reduction goals of 42.5%, but in combination with hybrid and/or CFRCs material replacement and lower weight window solutions, it will reduce the weight of the door structure to the required levels.

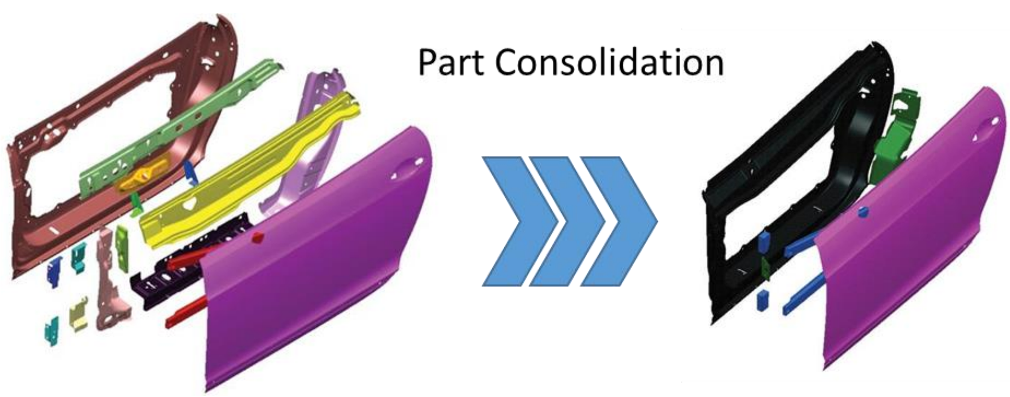


Figure II.2.3.3. Composites allow part consolidation, further reduces cost and weight. Source: Composites World [1].

Our hybrid solution will evaluate a variety of material solutions, including glass and CFs. Fiber modulus and strength depend on the fiber selection with specific properties being the highest for CFs. Design solutions without cost consideration will use 100% CFs and provide the best structural performance at the lowest weight. A hybrid design will incorporate alternative fiber solutions at a lower-cost and meet structural performance. Our optimal design will consider all options and will meet structural requirements and cost and weight targets.

Lower-density glazing (such as polycarbonate glazing) has been recently developed for automotive applications. Transparent polymers can be easily molded into complex shapes, and it offers a 50% weight-savings compared to standard glass solutions. The new materials have been demonstrated in both concept and production cars, including the Chevrolet Volt, Hyundai European Design concept cars, the Mercedes SMART, and Toyota V (station wagon version of the Prius) vehicles [2]. New window solutions also address the requirement for improved cabin comfort. Because glazing thicknesses have been reduced to save weight, the noise level within the car has increased. Integrating transparent acoustic layers within the glazing can be used to increase damping performance and thinner and lighter-weight glazing can be employed without compromising cabin comfort or safety. Polycarbonate glazing enables new design concepts because complex geometry windows can be fabricated. Polycarbonate glazing with integral ribs lock the parts onto the vehicle or support other features. This program will evaluate a polycarbonate solution, which should not only impact the weight of the glazing, but the overall design of the composite door solution. This will simplify assembly and have the potential to lower the cost and weight of the total door solution.

All considered concepts will be evaluated at the component and full-door level using structural FEA tools. The composite laminate structure can be varied and will change the anisotropic stiffness and strength behavior of the part. The selection of fiber materials will impact performance and cost. Optimization of the layups, materials, and geometries needs to result in a manufacturable design at minimum weight while meeting all design requirements. The team has significant experience in design and analysis using commercially available structural static and dynamic FEA tools for vehicle structures that will be key for evaluating and optimizing the designs.

Crashworthiness will be evaluated using LS-DYNA, allowing simulation of the door and full vehicle under dynamic conditions. In particular, we will consider the crash performance under side-impact meeting Federal Motor Vehicle Safety Standard 214's protection requirements (other Funding Opportunity Announcement crash scenarios will be considered). The simulation will evaluate inward deflection as a function of time during impact for the baseline steel door and our composite solution. A conservative design goal would require the composite solution provide a deflection profile that stays below the transient intrusion levels of the steel baseline door. This would ensure the safety mechanisms (such as the side airbag) are able to be deployed in time and space and the passenger is protected in case of a side collision. UD-CCM has significant experience with crash predictions and under a current National Highway Traffic Safety Administration program evaluates composites for a steel B-pillar replacement. Strain-rate-dependent material properties for composites are available; however, additional properties for the HP-RTM resins and fibers may have to be determined using coupon and subscale element testing. The test data will provide the programs with a database of material properties for crash designs.

The program will implement the HP-RTM process to fabricate sub-elements and full-size components. The process has been proven to produce Class A finished structural components at automotive rates. Cycle times of less than ten minutes have been demonstrated in production on the BMW i3 and i8; this program will further reduce cycle time and performance using the most recent advances in resins and reinforcements developed by our team members (i.e., a four- to five-minute cycle time would meet current vehicle production rates). Our partner, Krauss-Maffei, has implemented a production cell to automate the process. Structural components, sidewall panels, floor pans, front-end carriers, crash boxes, and CF design components are applications that have been implemented via HP-RTM. Fiber mats or fabrics are preformed and then positioned in the mold. A variety of low-viscosity polymers (such as polyurethane, epoxy, and polyamide) can be used as matrix material. The material components are mixed and heated in a metering system and injected into the heated mold. The resin quickly cures in the closed tool and the part can be demolded. Trimming occurs onsite. The HP-RTM process can produce parts with fiber content up to 70%. The process allows reuse of scrap material, improving material yield. Components manufactured using high-pressure RTM exhibit Class A surface quality and can produce high quality (low-defect) parts with an aesthetically pleasing C appearance. The procedure has been fully automated and is suited for series production from the manufacturing of preforms up to post-mold processing. The program will use the existing HP-RTM as the baseline process, evaluate opportunities to reduce cycle time through innovative new materials (Saertex and Hexion), and evaluate new process improvements (Krauss-Maffei, UD-CCM, and TPI).

New resin materials are currently being developed at Hexion and will be optimized for this program. These resins (e.g., EPIKOTE™ 05475) and appropriate curing agents have low initial viscosity (below 100 centipoise) and allow rapid infusion of reinforcement during the injection phase of the HP-RTM process [3]. The rheology of the EPIKOTE resin with three different curing agents is discussed in Hillermeier et al. [3] and shows the ability to control the viscosity profile, while ensuring rapid cure without significant exothermic reaction of the polymer. Recent advances show full property translation and rapid (i.e., snap) cure in less than two minutes at elevated temperature. The low-viscosity profile allows reduced injection pressure throughout the infusion cycle, relaxing the requirements of the preform, tool, mixer, and press. This, in turn, reduces preform distortion, cycle time, and capital cost.

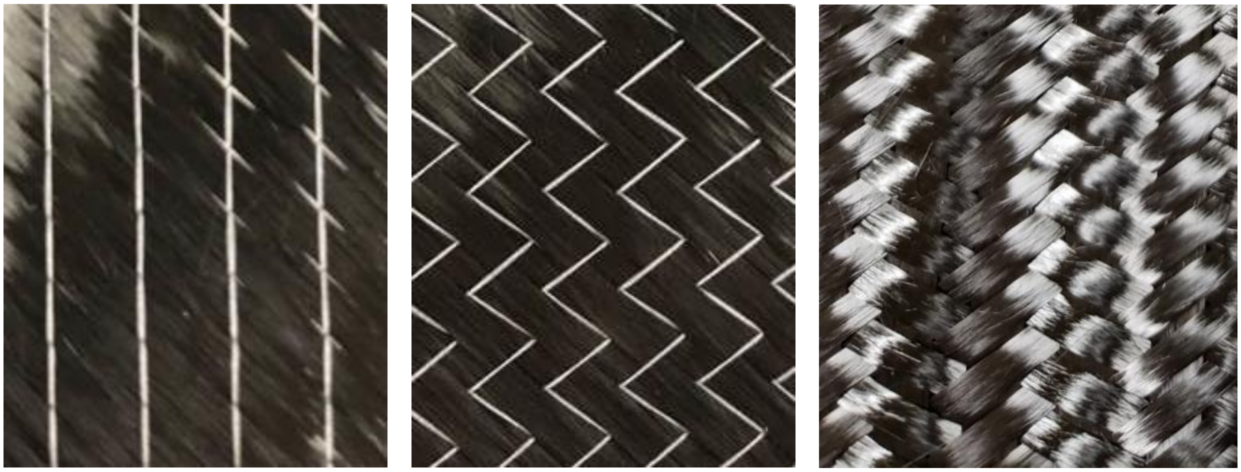
Non-crimp fabrics (NCFs) provide the best fiber property translation and, using multiaxial systems, can be combined in a preform used in the production of large series vehicle components. These preforms are manufactured to the correct geometry and fiber layup, allowing rapid placement of the reinforcement into the HP-RTM tool. This enables minimum cycle time during the process, paired with the high quality of the final product. It is important to optimize the preform to reduce scrap material and lower material cost. Our partner, Saertex, is the worldwide leader in tailor-made NCF materials and they will support development of low-cost preforms for this program.

A key challenge of the HP-RTM is the design of the mold and preform to ensure full infusion of the polymer into the reinforcement. Tooling cost is a significant capital expense because applied pressures are high, and the tool is expected to last over the entire production run. UD-CCM is an expert in modeling the infusion behavior in liquid molding of hybrid preforms with complex geometry. The permeability and drapability of the reinforcement, as well as the rheology of the resin, are key material properties and are needed to allow optimization of the injection port locations and resin pressure cycle during infusion processing. We will evaluate the feasibility of the proposed designs to be manufactured and optimize the mold features for successful infusion, eliminating any required tool changes due to resin infusion issues. The program will ensure manufacturability of the proposed concept with HP-RTM and use virtual process tools to optimize tooling and infusion approaches. Tooling cost for HP-RTM is a significant investment and can only be amortized over a large production run. Conventional RTM processing of prototypes with equivalent part properties will be conducted as part of our risk reduction strategy.

The performance of our designs will be evaluated at the coupon, sub-element, and full-door component level. This will include structural performance testing (i.e., static and crash) and other functionalities such as durability to environmental exposures and NVH. Our team has existing testing capabilities in these areas and a comprehensive test plan will be developed as part of the program. Coupon testing is needed to characterize the mechanical and microstructural (i.e., void content and fiber volume fraction) properties of the hybrid composite design made with the Hexion resin and HP-RTM process. Other data (such as durability, acoustical damping, and environmental performance) may need to be generated and may require larger component testing.

Results

FY 2019 started with our waiting for new materials for improved door inner preform drapability. The preform materials will include a chain stitch, a tricot stitch—which allows for greater drapeability or shearability—and a braided broadgood with good properties, as shown in Figure II.2.3.4 (a)–(c). These new material forms should improve drapability and contouring and reduce the amount of wrinkling seen in the preform.



(a) (b) (c)

Figure II.2.3.4. Preform materials types: (a) chain stitch; (b) tricot stitch; and (c) braided broadgood fabric. Source: TPI Composites.

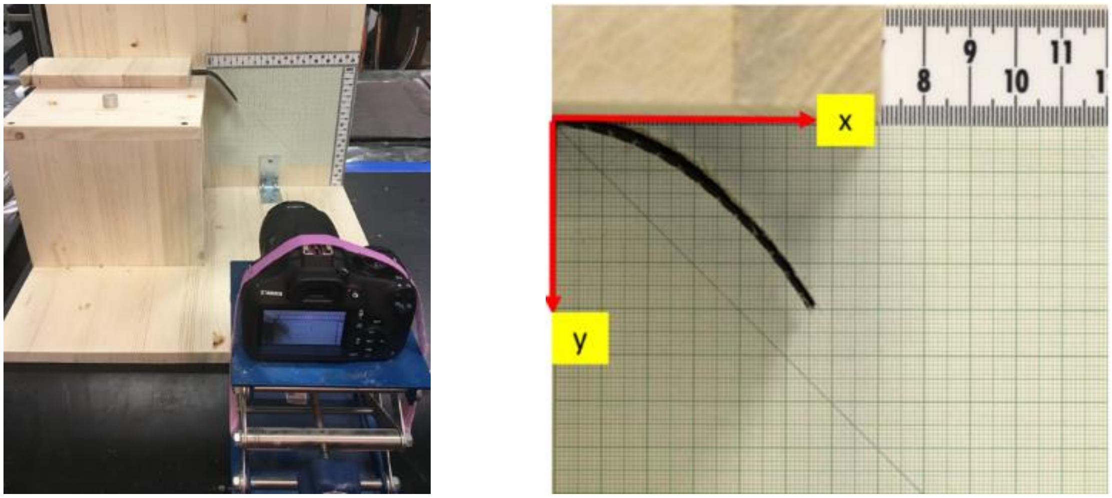
During the second quarter of 2019, the team worked on the following tasks: (1) applying draping models to model the preforming operation of the door inner; and (2) development of an optimization framework to maximize the structural performance of composites with minimum mass. The draping models developed in a previous DOE-funded project to GM (Contract No. DE-EE0006826) for developing NCFs were applied here. In parallel, a multi-variable optimization of a laminated composite beam subjected to a three-point bend test was investigated. The composite hat section beam layup was optimized with respect to two distinct requirements: (1) maximizing the peak load; and (2) maximizing the energy absorption (i.e., the area under the force-displacement curve). Subsequently, two layup designs optimizing the two requirements stated above were selected. The layup angles for these beams were modified slightly to match with the angles in the available fabrics. Composite beams were molded using these modified layups and experimentally evaluated. To validate the results, the predictions for the load versus displacement curves for these optimum solutions were compared with the experimental results. Good correlations were observed validating the developed models.

Draping Simulations

The draping simulation model used here involves modeling the fabric with independent behavior in three different modes, such as in-plane, bending and shear. Fabric characterization for bending and shear are essential for modeling. Following sections provide the details about the characterization tests.

Bending Stiffness Evaluations

The bending stiffness of a fabric is often measured using a cantilever beam bending apparatus, in which the fabric is allowed to bend as a cantilever beam under its own weight. ASTM D1388 provides a description of the method for making these measurements. The apparatus used for taking these measurements is shown in Figure II.2.3.5 (a). The bending stiffness can be calculated since it is related to the curvature of the deformed fabric as it bends under its own weight. To carry out the measurements, the fabric was cut into a 25 mm × 229 mm (1 in. × 9 in.) strip and carefully placed onto the apparatus without disturbing the fibers. The fabric was then covered by the top movable sliding board. This board was then slid across the top plate to the predetermined overhang length and the sample was allowed to drape to its natural curve, as shown in Figure II.2.3.5 (b). After the target overhang length was reached, high-resolution images were captured in order to measure the draping curvature of the fabric at this overhang length. A 70 mm overhang length was selected for the measurements along the stitching direction, and 90° to the stitching direction, while a 110 mm overhang length was selected for the measurements along the fiber direction. The bending stiffness could be determined using the equations available in the literature to describe the fabric draping curvature.



(a) (b)

Figure II.2.3.5. (a) Bending stiffness measurement apparatus. (b) An example image used for measuring curvature and the extent of bending. Source: TPI Composites.

Bias-Extension Experiments

The bias-extension test measures the load required to stretch fabric that is prepared with the tows oriented at +/-45° with respect to the loading direction. The bias-extension test was carried out using specimens of both NCF fabrics. Data was collected for specimens that were 127 mm wide. This data was used in the calibration of the PAM-FORM material card. In order to simplify the analysis of the data, the length of the specimen was three times greater than the width. Therefore, the tested area of the fabric was 127 mm × 381 mm (5 in. × 15 in.). Since the specimens required an extra 38 mm at each end in order to mount them in the grips of the test frame, the actual specimen length was 457 mm for the 127 mm wide specimens. Physical testing was performed on an Instron 5582 load frame using series 2710–116 side action grips with 25 mm × 76 mm grip faces. Great care was taken not to disturb the original fiber crossing angles of the test specimens as they were prepared and mounted in the testing frame. The grip separation rate for the 127 mm specimens was 30 mm/min.

The shear behavior of the fabric was measured with both of the stitches acting in compression and tension, respectively. When the stitches are in tension, the shear stiffness is significantly higher than the case with the stitches in compression. The nonlinear shear behavior illustrated in Figure II.2.3.6 was used in the model.

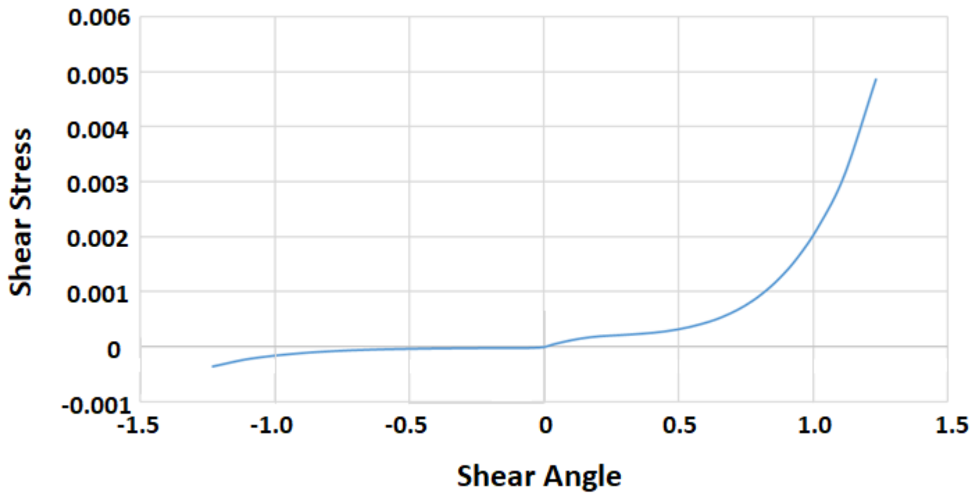


Figure II.2.3.6. Nonlinear shear behavior used in draping modeling. Source: OEM Partner.

Draping Simulation Results — Comparison with Experiments

A material model in PAM-FORM framework was developed using the fabric characterization tests performed above. Draping simulations were conducted and the simulations are compared with experiments for different preforms, as shown in Figure II.2.3.7 for preform 1 and Figure II.2.3.8 for preform 2.

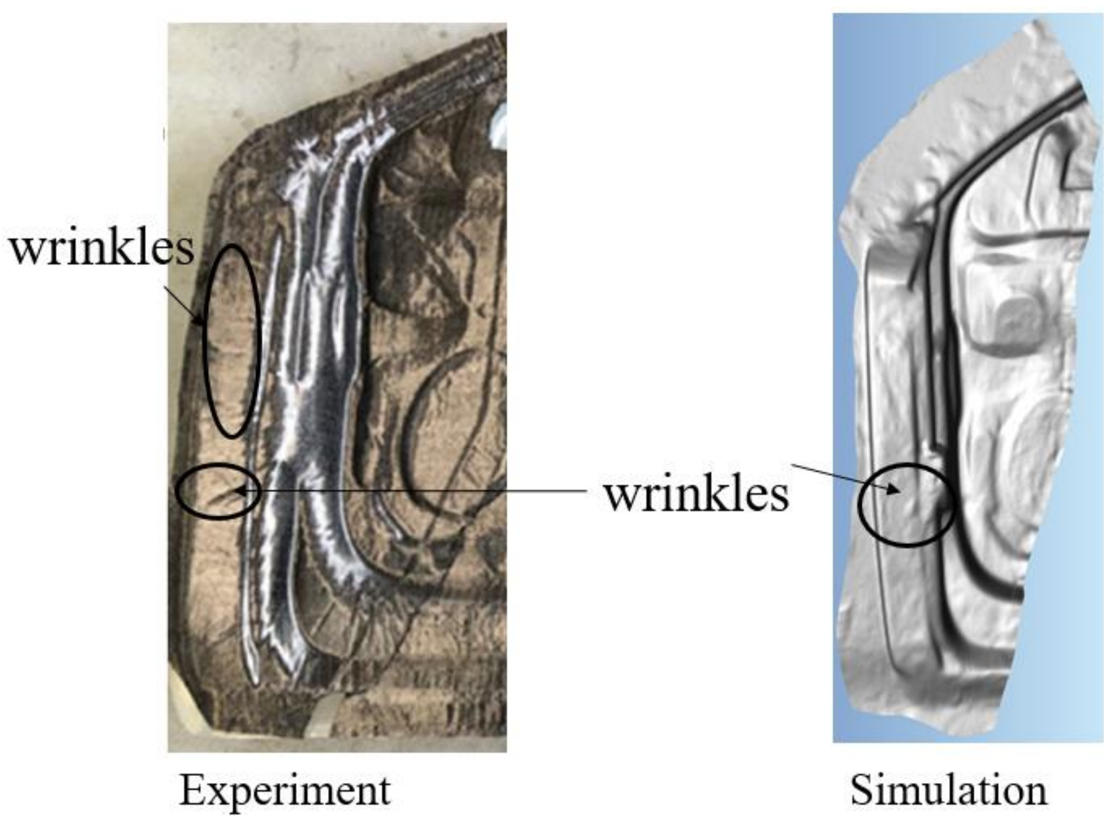


Figure II.2.3.7. Comparison of draping experiment and simulation for the preform 1. Source: OEM Partner.

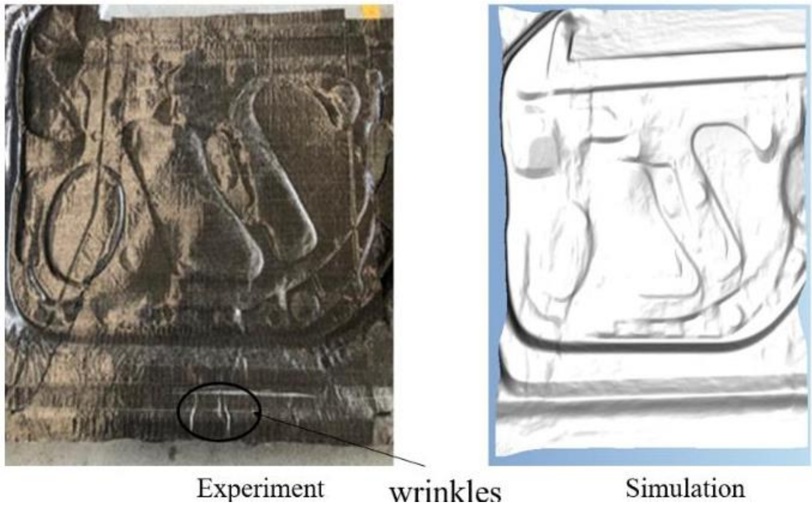


Figure II.2.3.8. Comparison of draping experiment and simulation for preform 2. Source: OEM Partner.

Based on these preliminary results, no clear conclusions about the wrinkle correlations could be made. This could be due to the difference in blank size used for preforming, draping conditions (i.e., hand versus mating tools), material difference between the draped material and the material used for characterization.

Simulation-Based Optimization

Simulation-based optimization has become a powerful tool in the automotive industry to drive the safety designs virtually for automobiles. In the present work, the optimization framework was developed using Altair HyperStudy Software (a multidisciplinary design and optimization software) coupled with LS-DYNA as the FE solver. For the optimization, to avoid local optimum traps, the global response search method was adopted and its efficiency for the optimization of composite structures was assessed in this study. This method combines adaptive response-surface-based optimization with global searching capability. It is able to efficiently provide global or close-to-global optimum solutions in a highly nonconvex design problem. For this optimization, the composite hat section beam layup design for a three-point bending was optimized with respect to two objective functions: (1) maximize the peak load; and (2) maximize the energy absorption. Figure II.2.3.9 shows the top, back and end views of the composite beam used for the study.

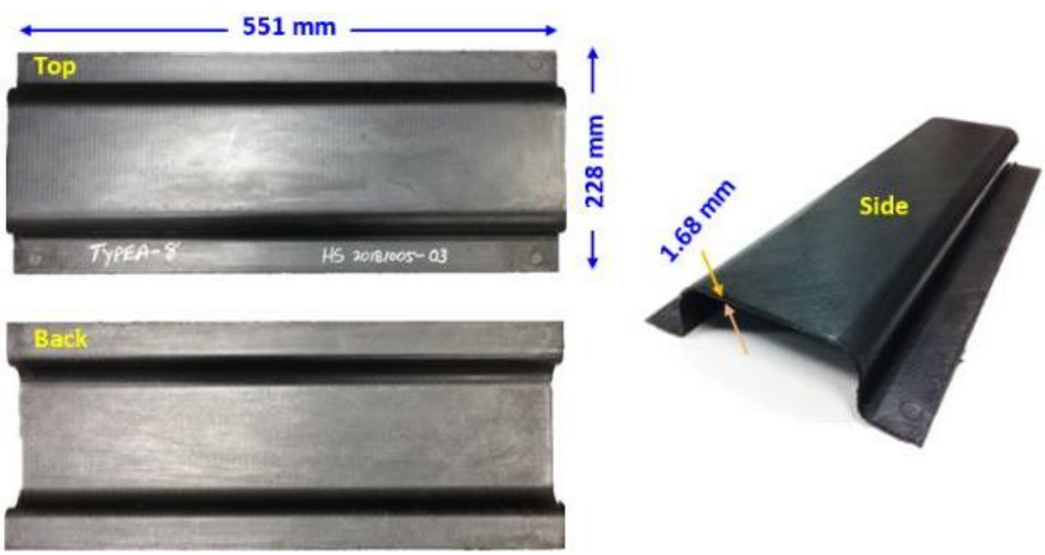


Figure II.2.3.9. Single hat section beam used for the study. Source: OEM Partner.

Optimization Results

Two design points (i.e., design 1 and design 2), circled in Figure II.2.3.10, were selected as the extreme points of the objectives (e.g., one design point for each objective—peak load and energy absorption) to verify the optimization results through the use of three-point bend tests. The NCF material used in this study (i.e., C-PLY SP BX 240 T3.3 50K HS from Chomarat Inc.) was chosen for molding the beams. As only certain layup angle choices were available (i.e., 0/90, +45/-45 and -45/+45), designs 1 and 2 were adjusted to use the available fabric angles. The design 1 layup was altered from $[-84/6/-68/22/90/180]_s$ to $[(90/0)_3]_s$ and denoted as Beam D. The design 2 layup was modified from $[-56/34/88/178/86/176]_s$ to $[\mp 45/(90/0)_2]_s$ and denoted as Beam H. Table II.2.3.1 summarizes the experimental values and the simulation results obtained for Beams D and H, respectively. The simulations results were re-run using the altered layups.

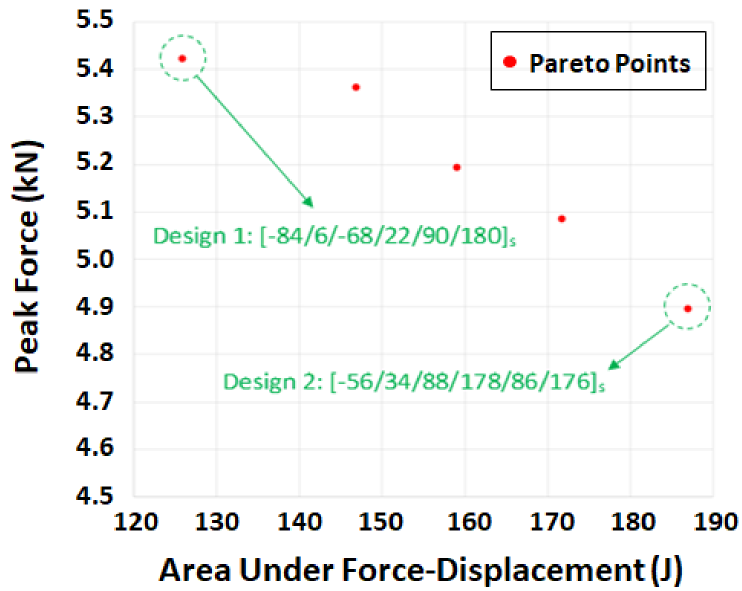


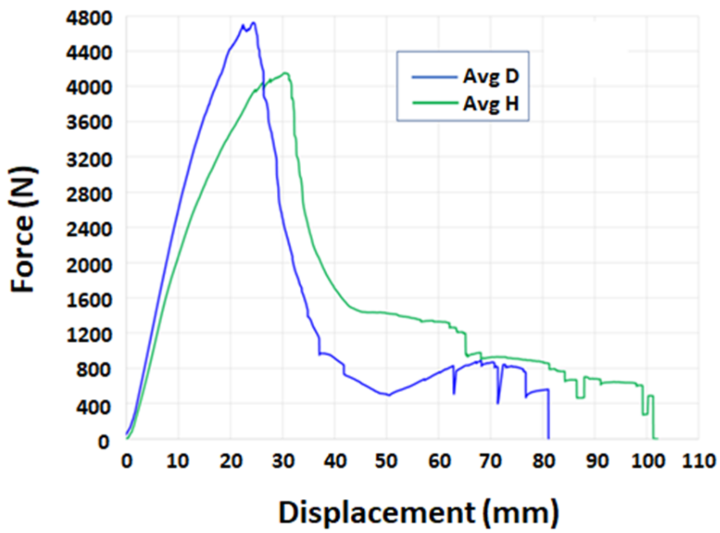
Figure II.2.3.10. Selected design points for conducting flexural tests. Source: OEM Partner.

Table II.2.3.1. Optimization Results.

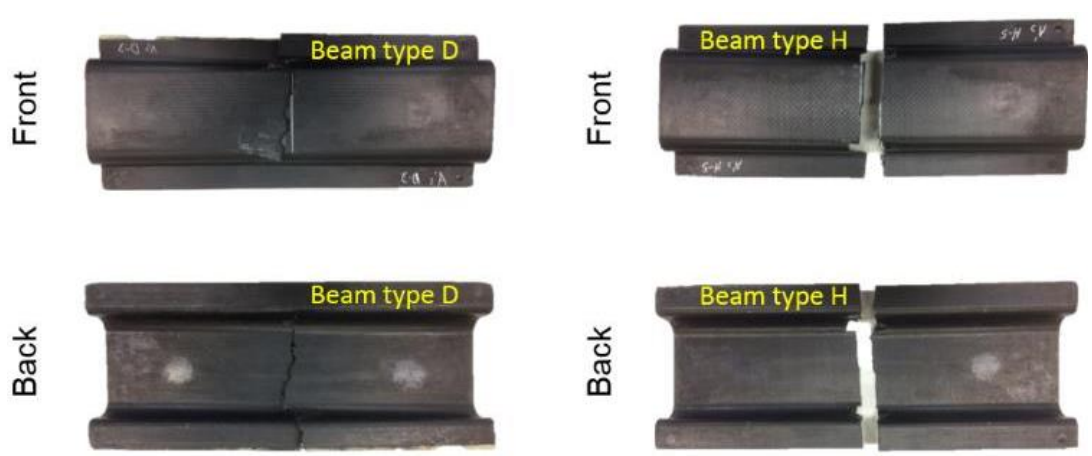
Design	Approach	Layup	Peak Load (kN)	Area of force-displacement Curve (J)
Design 1	Simulation-based optimization	(-84/6/-68/22/90/180)s	5.4	126
	Simulation (Beam D)	(90/0/90/0/90/0)s	4.5	131
	Experiment (Beam D)	(90/0/90/0/90/0)s	4.7	127.6
Design 2	Simulation-based optimization	(-56/34/88/178/86/176)s	4.9	187
	Simulation (Beam H)	(-45/45/90/0/90/0)s	4.15	184
	Experiment (Beam H)	(-45/45/90/0/90/0)s	4.4	164

Validation of Optimization Results

Quasi-static flexural bending evaluations were carried out for the two different beam types—Beam D and Beam H. Five samples of each design were molded and tested. Figure II.2.3.11 (a) compares the average force-displacement curves and the typical failure patterns of Beams D and H. Each representative curve is the average result of the three best tests, as some of them did not give good results due to warpage of the beams after molding because of unbalanced laminates, leading to the beams not conforming properly to the test fixture. It should be noted that for a given beam type, once the specimen fails, the data points following the failure are not considered in calculating the average curve. As expected, both peak force and initial stiffness were higher for the Beam D as compared with Beam H. Beam H exhibited more "ductile" behavior as compared with Beam D, due to the use of the biaxial layup and the resulting ductile shearing behavior of the resin. The energy absorption calculated from the area of the force-displacement curve for Beams D and H were 127.6 Joules and 164 Joules, respectively. These values were obtained by averaging the areas under the force-displacement curves of the three tests for a given beam type. It should be noted that both of the beam types failed into two pieces during the testing, as shown in Figure II.2.3.11 (b).



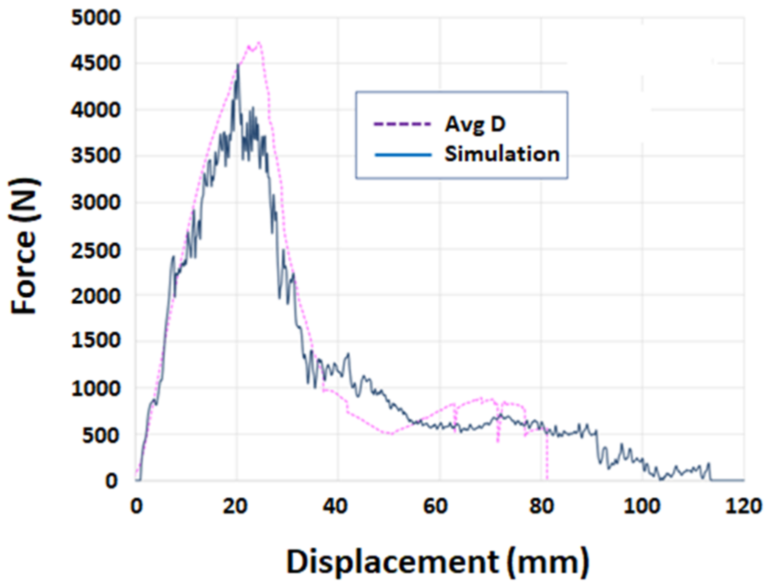
(a)



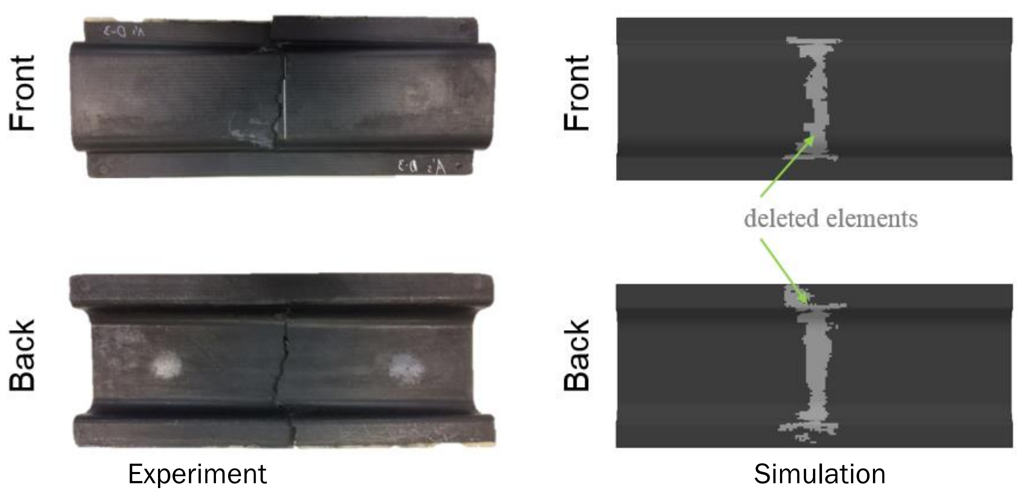
(b)

Figure II.2.3.11. Experimental three-point bend test results for the two beam types: (a) average force-displacement trends; and (b) damage pattern representatives. Source: OEM Partner.

Figure II.2.3.12 and Figure II.2.3.13 compare the force-displacement trends and the damage patterns obtained from the simulations and the experiments for Beams D and H, respectively. The force-displacement curve obtained from the experiment and the simulation showed close agreement for both of the beam types. The predicted peak load for Beam D was about 4.25% lower than the average experimental value, whereas it was about 5.6% lower for Beam H. The predicted damage pattern was in excellent agreement with the experiment for both beams, as shown in Figure II.2.3.12 (a) and Figure II.2.3.13 (a), respectively. For Beam D, the area under the force-displacement curve obtained from the prediction and experiment was 131J and 127.6J, respectively (e.g., a 2.6% difference). For Beam H, the area under the force-displacement curve between the prediction and the experiment was 184J and 164J, respectively (e.g., a 10.9% difference). For Beam H, this is because the damage in the simulation did not extend completely across the entire beam as was observed in the experiment. Figure II.2.3.13 (b) and Figure II.2.3.13 (b) show the damage patterns for Beam D and Beam H, respectively. However, this difference in results is deemed to be acceptable, given the challenges in predicting the energy absorption of the composites materials. Future work will be focused on fine-tuning the element deletion criteria for ductile laminates in order to improve the predictions.

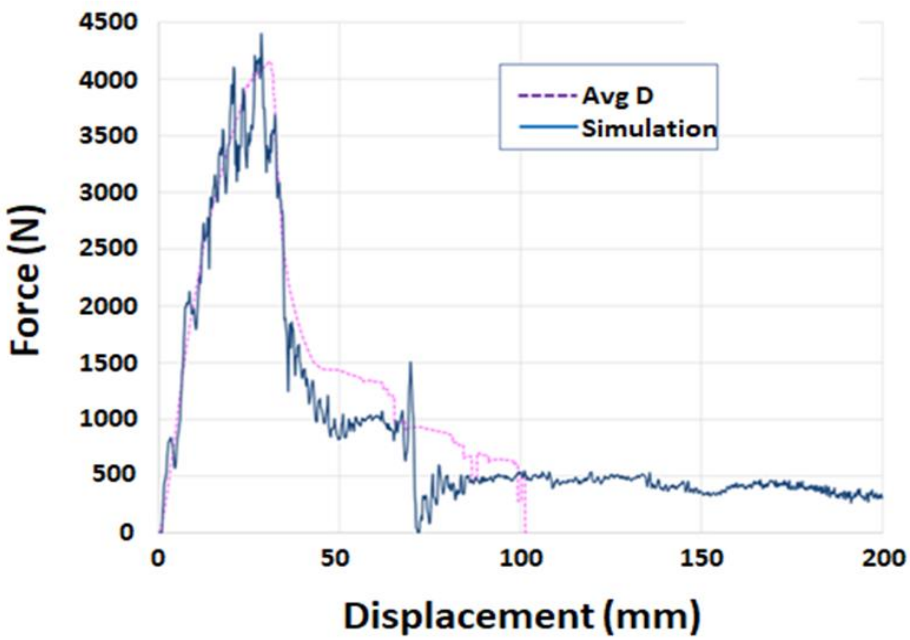


(a)

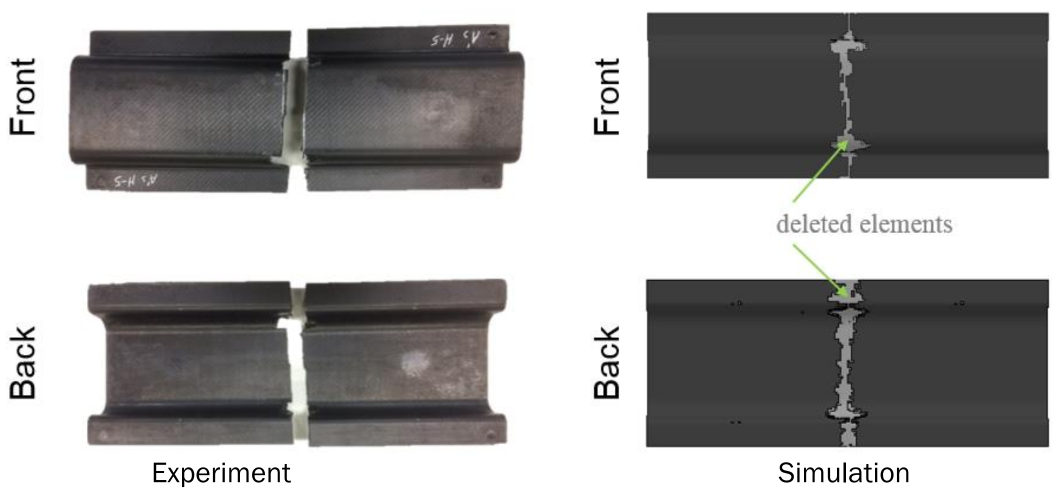


(b)

Figure II.2.3.12. Comparison of the flexural test and the simulation result for Beam D: (a) load-displacement trend; and (b) damage pattern. Source: OEM Partner.



(a)



(b)

Figure II.2.3.13. Comparison of the flexural test and the simulation result for the Beam H: (a) load-displacement trend; and (b) damage pattern. Source: OEM Partner.

Re-Manufacture of Door Inner

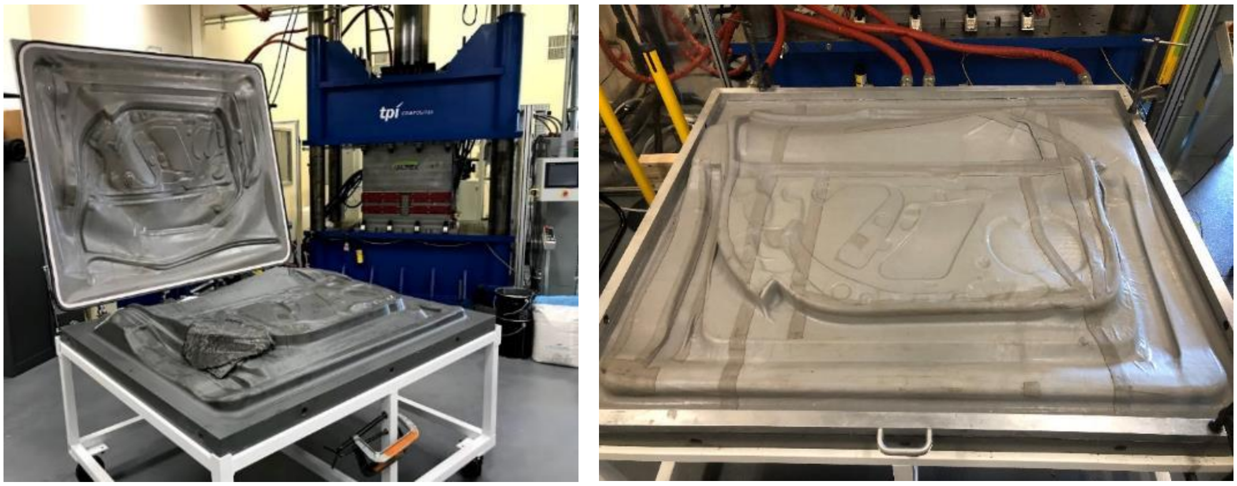
Due to issues in design quality short-falls discussed previously during last year's annual report, the door inner parts were remade at Fraunhofer Project Centre for Composites Research in London, Ontario, Canada.

Fabric Materials

For the remake of the inner door panels, three different types of materials were utilized. The first was an NCF supplied by Chomarat, which has a thermoplastic veil attached to one side to act as a stabilization binder during preform consolidation. The second was made from the same Chomarat NCF material; however, the thermoplastic veil was replaced by a thermosetting power binder made by Hexion. The third was provided by A&P Technology. This material is a woven carbon product that is then slit to produce a broadgood fabric. This material was also supplied with the Hexion thermosetting powder binder applied.

Preform Creation

TPI cut all the materials for the door inner in advance at our Rhode Island facility and shipped them to the Fraunhofer Project Center in London, Ontario, Canada. The individual plies of various weights and angles were cut via an Eastman automated ply cutter. Then each laminate stack was created by hand to get the correct orientation of the stack. These plies were then laid on top of a heated Al tool with a silicone vacuum bag for the purpose of consolidating the fabric, as shown in Figure II.2.3.14 (a) and Figure II.2.3.14 (b). The Al preform tool was designed to create all five preforms required for the door inner.



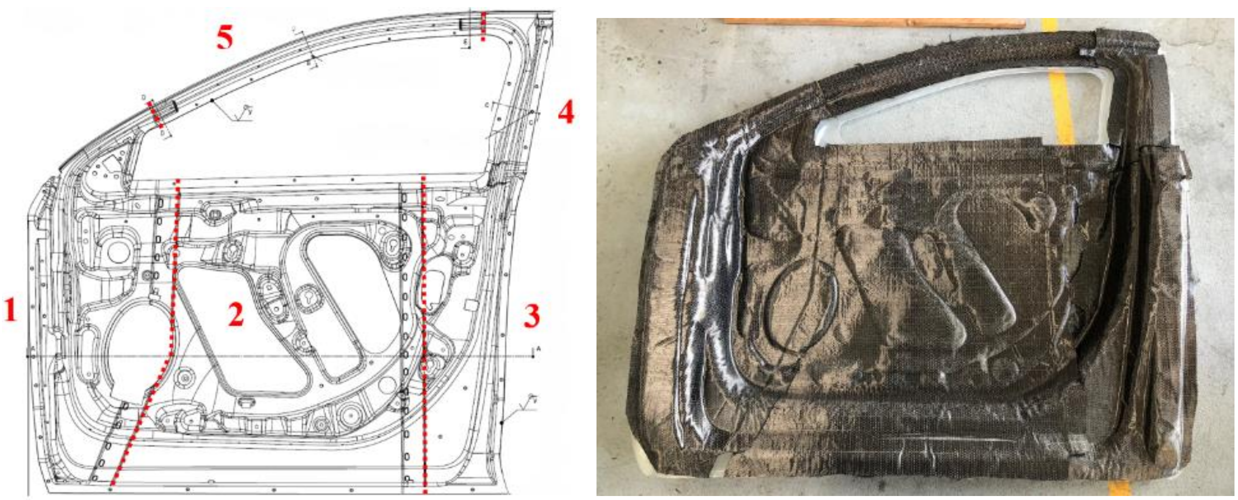
(a) (b)

Figure II.2.3.14. Al preform tool with the silicone vacuum bag in (a) the open position and (b) the closed position. Source: TPI Composites.

The materials were placed onto the tool and smoothed by hand and darted where necessary to allow the material to lay flat. Then the silicone bag was closed, and a vacuum was applied. The tool was then heated above 265°F to allow the binder materials to hold the layers together. Photos taken during the preform fabrication process are shown in Figure II.2.3.15 (a) on the mold and Figure II.2.3.15 (b) after consolidation and trimming. Prior to removing the preforms, the tool was cooled to stabilize the material before removal. Unlike the previous preforms that were produced and molded, these preforms were all made using a separator fabric between certain layers to allow the separate preform to be lap-joined to each other. Previous preforms were only tab-joined, which led to unfavorable molded part results. The resulting preform and the inner door design are shown in Figure II.2.3.16 (a) and Figure II.2.3.16 (b), respectively.

(a) (b)

Figure II.2.3.15. Preform fabrication (a) on the mold and (b) after consolidation and trimming. Source: TPI Composites.



(a) (b)

Figure II.2.3.16. Preform breakup (a) for the door inner (b). Source: TPI Composites.

Molding

The door inner mold was shipped to Fraunhofer Project Center in London, Ontario, Canada, pictured in Figure II.2.3.17. The Fraunhofer facility has a Dieffenbacher Compress Plus press combined with a Krauss-Maffei resin dosing system for manufacture of HP-RTM composite parts. TPI arrived on July 29, 2019, to begin molding the new preforms. At that point, the tool was preheated and connected to the press and we were ready for the trials.

Figure II.2.3.17. The Fraunhofer facility. Source: Fraunhofer Project Center.

Intrusion Beam Hats, Preform Creation and Molding

Intrusion beam hats, as shown in Figure II.2.3.18, were produced via HP-RTM at TPI Composites Advanced Transportation Composites Center in Fall River, MA, USA.

Figure II.2.3.18. HP-RTM molded intrusion beam hats. Source: TPI Composites.

The preforms for the intrusion beams were made using an Al preforming mold, which allowed the laminate stack to be vacuum-bagged to contour. Once the fabric was contoured, the mold was shuttled through a conveyor oven to heat the preform/mold to allow the binder to fix the preform into the contour. These preforms were then hand-trimmed to fit into the HP-RTM mold cavity shown in Figure II.2.3.19.

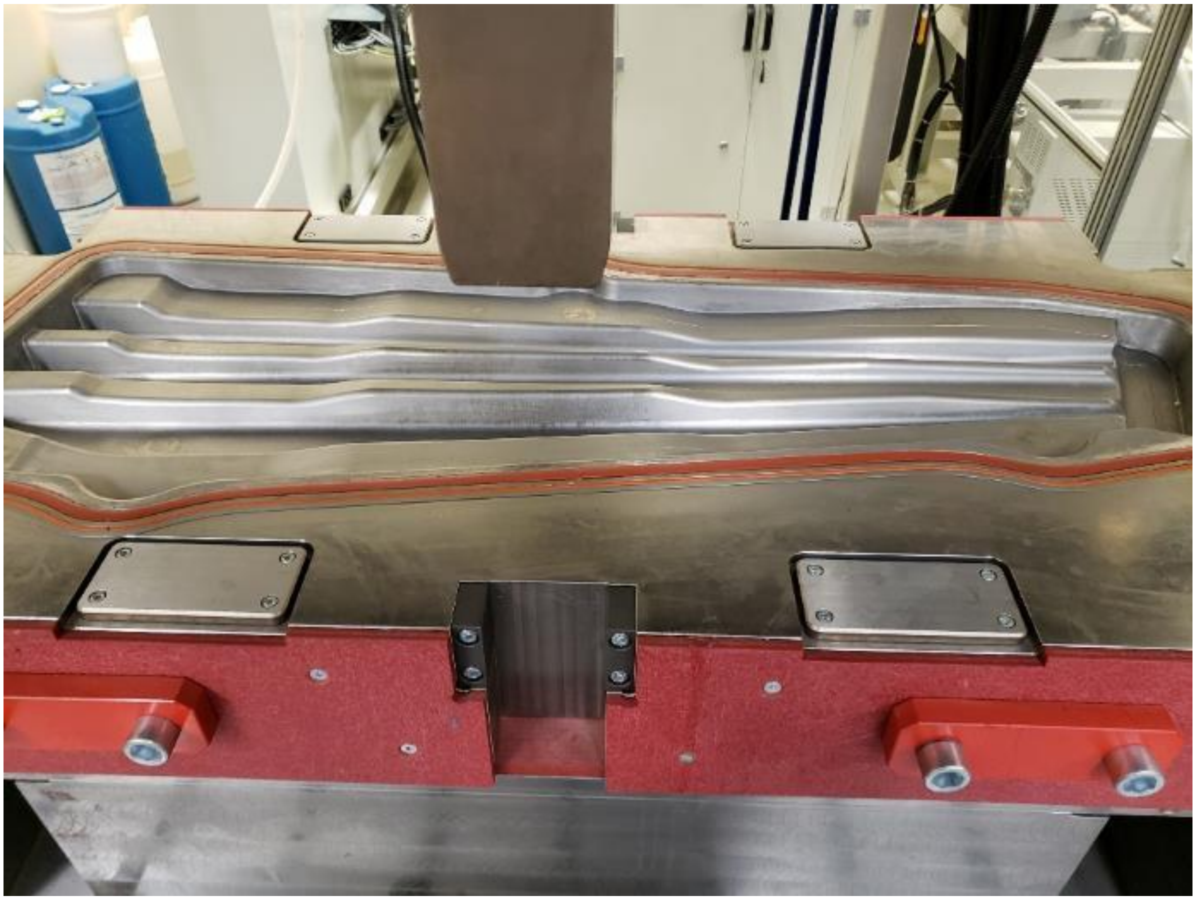


Figure II.2.3.19. The mold cavity for the HP-RTM intrusion beam hat. Source: TPI Composites.

The part-to-part cycle time was approximately six minutes, which included hand-loading the preforms, mold-closing, injection, cure, mold-opening, part extraction, and mold-cleaning.

Issues, Risks, Mitigation

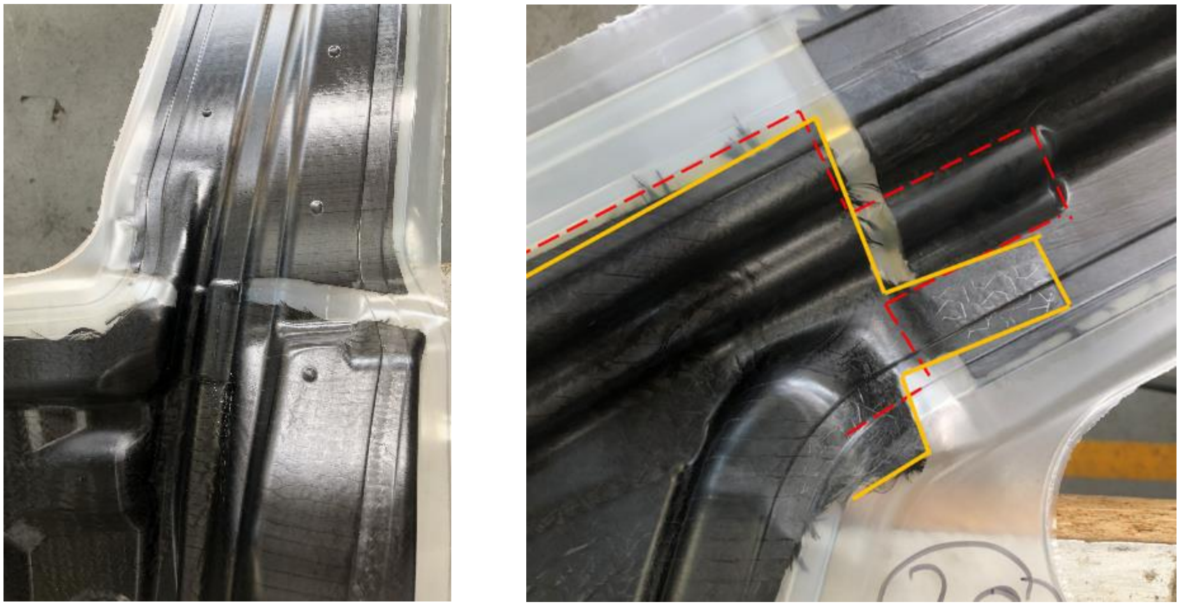
Dry Areas

Although the parameters used to mold these new preforms were identical to those used to produce the previous parts, the molded part quality was not as good. Many of the produced parts had dry areas in the center of the part where the preforms had bunched, as observed in Figure II.2.3.20. Unfortunately, due to the limited number of preforms available, we were not afforded the ability to really make any process tweaks or refinement to try and improve the part quality.

Figure II.2.3.20. Dry area. Source: TPI Composites.

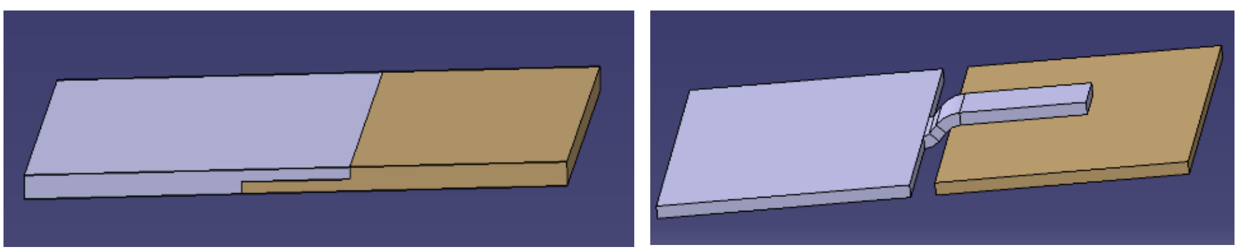
Preform Overlaps

As was previously noted, the original tab-joined preform design caused issues with resin-richness and movement, as shown by the photographs in Figure II.2.3.21 (a) and Figure II.2.3.21 (b), respectively. The new lap-joined preform approach compared to the previous tab-joint approach as shown in Figure II.2.3.22 (a) and Figure II.2.3.21 (b), respectively, was very successful in eliminating these issues, possibly because the higher drapability of the woven material over the NCF was much better at shearing and conforming to the part details.



(a) (b)

Figure II.2.3.21. Sliding preform at the mirror mount showing: (a) the resin-rich area; and (b) the preform out of position. Source: TPI Composites.



(a) (b)

Figure II.2.3.22. Preform joint designs for: (a) the lap-joint for the new preforms; and (b) the tab-joint for the old preforms. Source: TPI Composites.

General Preform Wrinkling

Like the previous parts that were produced, wrinkling of the preform occurred across the part of the NCF preforms as shown in Figure II.2.3.23. The wrinkling was independent of the type of binder, thermoplastic veil, or thermoset powder, which was used to create the preform. However, the woven (braided) material did not exhibit any wrinkling of the preform. It is believed that due to the higher drapability of the woven material over the NCF, this material was much better at shearing and conforming to the part details.

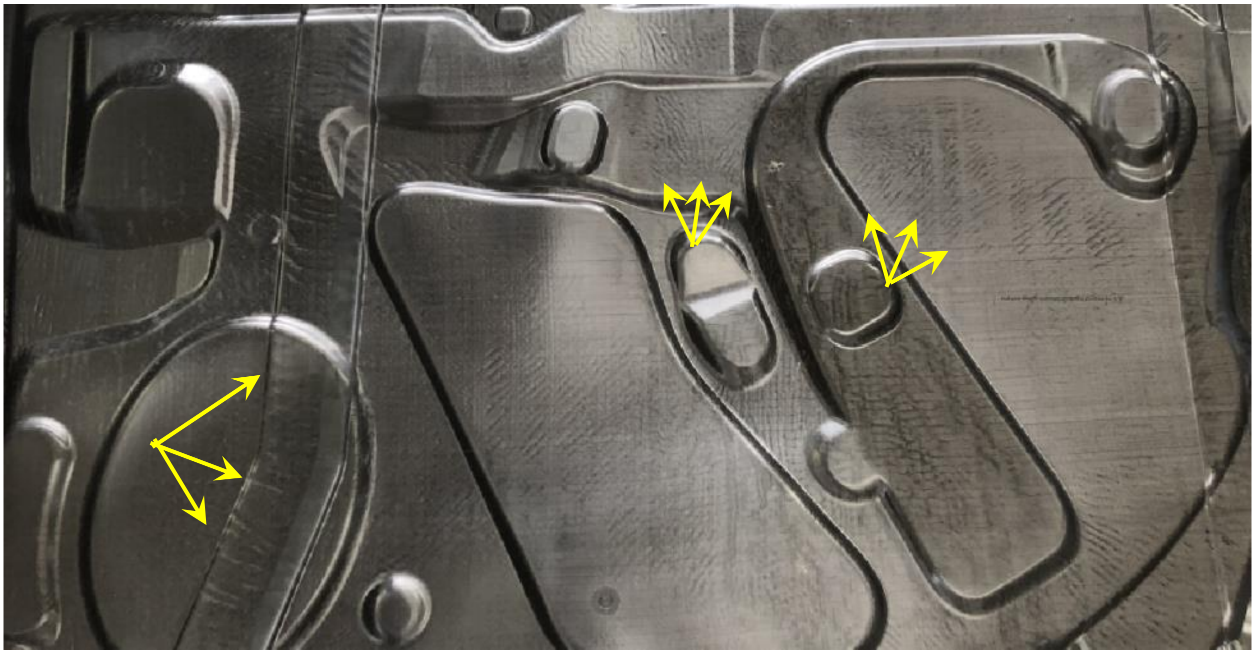


Figure II.2.3.23. Part wrinkling in the NCF preform. Source: TPI Composites.

The next steps are to have the molded inner panels machined. Following inner panel machining, the doors will be assembled and boned together into the final configuration. Fully assembled doors are scheduled to be completed and shipped for static testing with the dynamic impact testing to occur before the end of the project.

Status to Target

The design solutions presented in this report represented a cost of $715 per door at a mass of 22.8 kg (or 50.2 lbs.) as depicted in the charts shown in Figure II.2.3.24 and Figure II.2.3.25 (a) and (b). This represents a savings of 13.7 kg (or 30 lbs.) over the existing baseline door design. The cost increase of $138 per part and 30 lbs. of mass saved yields a $4.58 cost increase per pound of weight saved, exceeding the program targets. The total mass saved is 38% going from 36.5 kg to 22.8 kg. This target proves to be more difficult as the total mass of the door is included in this calculation. The window track/motor, latch, hinges, and other subassemblies represent 56% of the total mass of the door and they are harder to lightweight than the structure.

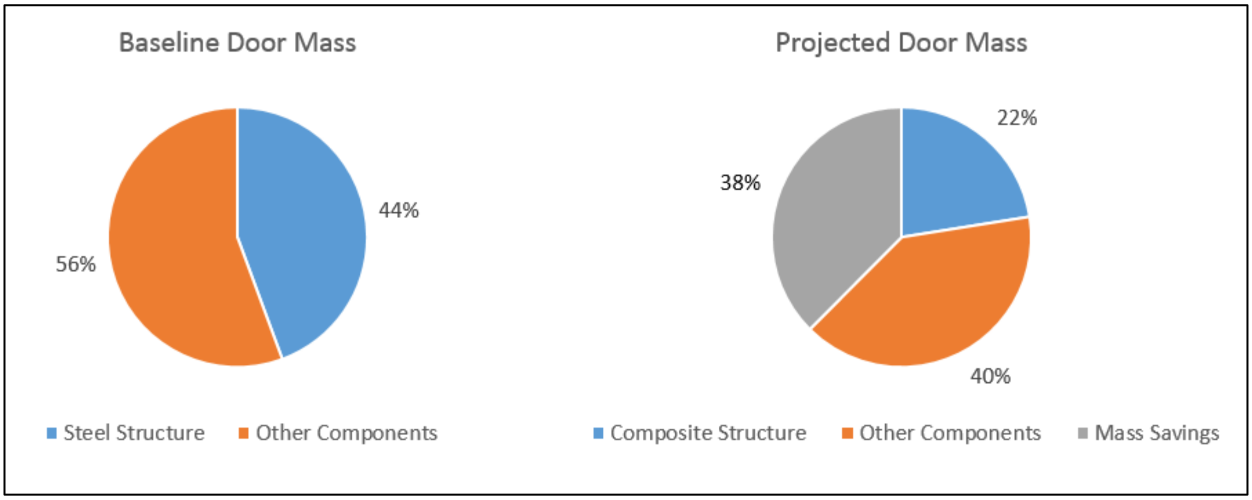
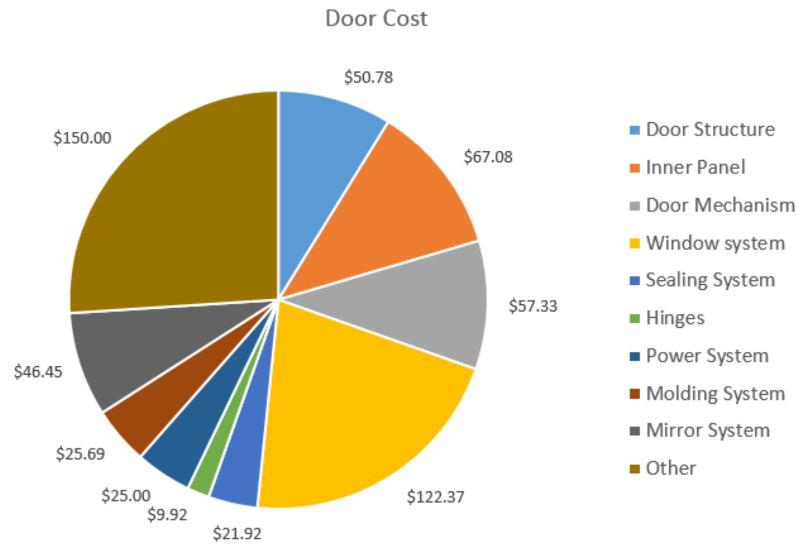


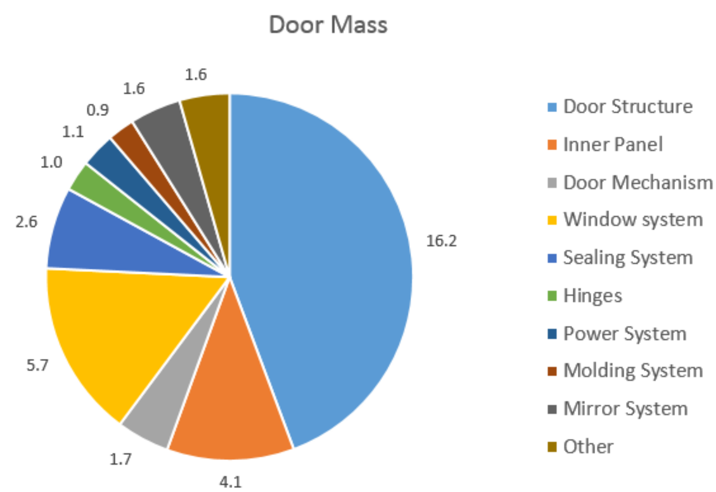
Figure II.2.3.24. Door mass breakdown. Source: TPI Composites.

Component	Cost
Door Structure	$ 50.78
Inner Panel	$ 67.08
Door Mechanism	$ 57.33
Window system	$ 122.37
Sealing System	$ 21.92
Hinges	$ 9.92
Power System	$ 25.00
Molding System	$ 25.69
Mirror System	$ 46.45
Other	$ 150.00
TOTAL	$ 576.54



(a)

Component	Current Mass [kg]
Door Structure	16.2
Inner Panel	4.1
Door Mechanism	1.7
Window system	5.7
Sealing System	2.6
Hinges	1
Power System	1.1
Molding System	0.9
Mirror System	1.6
Other	1.6
TOTAL	**36.5**



(b)

Figure II.2.3.25. Breakdown for: (a) the baseline door cost; and (b) the baseline door mass. Source: TPI Composites.

The optimized design as defined during the FY 2018 program yields a 38% mass save and a $5.47 cost increase per every pound saved. This is based on the input fiber, Zoltek Panex 35, at a cost of $7.75 per lb. Should the low-cost CF from ORNL be commercialized and realize an input fiber cost of $4.75, we could then exceed the cost target even further, getting down to as low as $4.33 per pound saved, as shown in Table II.2.3.2.

Table II.2.3.2 Status to Target.

Input CF Cost: $7.75/lb		Input CF Cost: $4.75/lb	
Optimized Design		ORNL Low-Cost Carbon Fiber Design	
Weight Reduction (lb.)	30.3	Weight Reduction (lb.)	30.3
% Reduction	38%	% Reduction	38%
Cost Increase	$165.72	Cost Increase	$131.13
Dollars/lb. saved	$5.47	Dollars/lb. saved	$4.33

Conclusions

We are close to the major goals of reducing part count and full-system weight by a minimum of 42.5% (38% achieved), the cost increase not exceeding $5 per pound of weight saved ($4.33 achieved with low-cost carbon fiber), and materials and processes meeting the production rate and performance requirements.

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2. Motavalli, J., 2011, “Shattering glass: Low-weight plastic car windows are coming,” *CBS Money Watch* (July), Available at: http://www.cbsnews.com/news/shattering-glass-low-weight-plastic-car-windows-are-coming/ (last accessed 5 December 2019).
3. Hillermeier, R., T. Hasson, L. Friedrich, and C. Ball, 2013, “Advanced thermosetting resin matrix technology for next-generation high-volume manufacture of automotive composite structures,” *SAE Technical Paper* 2013-01-1176.