THERMOPLASTIC CARBON FIBER REINFORCED BODY-IN-WHITE STRUCTURES FOR VEHICLE CRASH APPLICATION

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ABSTRACT

Carbon Fiber Reinforced Plastic (CFRP) composites are becoming one of the possible solutions for vehicles to achieve overall weight reduction in order to meet fuel economy and emission standards while maintaining safety requirements. Carbon fiber thermoplastic composites offer several additional advantages over their thermoset equivalents: higher levels of ductility and specific energy absorption, rapid processing and recyclability.

The Department of Transportation's National Highway Traffic Safety Administration (NHTSA) awarded the National Center for Manufacturing Sciences (NCMS) a contract to research potential materials and to evaluate their impact on vehicle crash safety and weight savings. In a joint research Project, the University of Delaware Center for Composite Materials (UD-CCM) and Bayerische Motoren Werke (BMW) investigated available computational tools for the design, optimization and manufacture of carbon fiber thermoplastic body-in-white structures for vehicle crash applications.

A vehicle B-pillar was developed to meet the FMVSS No. 214 standard, a US vehicle safety requirement for side impact. In addition, BMW internal structural integrity requirements as well as geometrical requirements were met. The design process demonstrated the capabilities of a computational tool chain, including geometrical design, carbon fiber layout, draping, material property management and dynamic impact simulation. Following this approach, a weight reduction of 60% compared to a metal baseline could be achieved.

A thermoplastic B-pillar was manufactured at UD-CCM using infusion as well as thermoforming processes for differing parts of the assembly, which could be scaled to meet industry requirements. In the final drop tower test series, the B-pillar was proven to meet all considered safety requirements. In addition the computational predictive engineering approach could be validated using the test results.

INTRODUCTION

Previous studies have shown that composite structures deform in a different manner than similar structural components made of conventional materials like steel and aluminum. The micro-mechanical failure modes, such as matrix cracking, de-lamination, fiber breakage etc. constitute the main failure modes of composite structures. These complex fracture mechanisms make it difficult to analytically and numerically model the collapse behavior of fiber reinforced composite structures.
However, they provide potential for weight saving while maintaining a high level of safety in vehicle crash applications.

Crashworthiness of carbon composites

Several studies [1] [2] have shown that carbon composites are superior to conventional metal structures with respect to energy absorption per unit weight in a dynamic impact event. Further investigations led to the conclusion that crash performance and energy absorption of composite structures are influenced by a wide range of design parameters as well as material properties and loading conditions [3]. Therefore the design and dimensioning of composite structures for vehicle crash application requires sophisticated computational models as well as a flexible, tailored design process.

Structural integrity is a main driver of dimensioning of body-in-white structures for crashworthiness. BMW conducted a series of investigations, showing that composite structures offer at least an equal level of safety compared to conventional materials, with regard to structural integrity subsequent to a crash event. [4]

Thermoplastic Carbon Composites offer specific advantages over their thermoset counterparts. Material properties of many available thermoplastic matrix materials offer greater ductility and thus may provide advantages concerning energy absorption in an impact event. In addition to the mechanical properties some thermoplastic composite materials show great potential for recyclability compared to most thermoset composites.

REQUIREMENTS

To obtain suitable performance goals for the composite B-pillar component, full vehicle crash simulations featuring a conventional steel B-pillar have been conducted to measure the amount of energy consumed by the B-pillar as well as the deformation behavior. It was assumed that as long as the composite B-pillar shows an equal or smaller intrusion during the course of the impact, equivalent or greater occupant safety can be achieved by applicable restraint systems.

In addition to the intrusion requirement, the need to ensure structural integrity after the crash event permits a valid B-pillar design from separating completely or de-bonding completely from neighboring parts during the crash.

DESIGN PROCESS

In this joint research UD-CCM und BMW aim to showcase a design process (Figure 1) suitable to support the above mentioned advantages thermoplastic carbon fiber materials offer, while addressing the challenge of computational modelling. This includes evaluation of commercially available software.

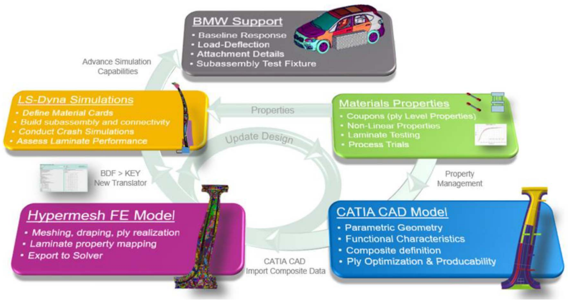

Figure 1. Design Process for Carbon Composite Components in Vehicle Crash Application (see also appendix 1).

Geometrical Design

A parametric CAD model of a simple B-pillar was developed utilizing a generic design derived from a BMW vehicle model. This model helped to establish the design space or envelope available for composite design and optimization. A wide variety of shapes and associated composite designs were evaluated. This led to the development of a two-part closed Hat section. This design considered two composite parts with a smooth “Spine” laminate bonded to a “Hat” laminate as shown in Figure 2.

Figure 2. Spine-Hat Adhesively Bonded Composite B-pillar.

The Spine was designed to survive the impact event without experiencing major failure, while the high-elongation nylon-based Hat structure absorbed the majority of the impact energy by means of deformation and crushing.

To achieve progressive crushing behavior, off-axis dominant laminates were prescribed in the Hat’s sidewalls. To reduce overall weight, the laminate thickness drops in the vertical axial direction as less material was needed in the less-loaded Hat upper section. Transition regions were automatically built between these regions using rules and ply transitions defined with the Grid Method in CATIA. The different composite regions and transitions zones of the Hat laminate are shown in Figure 3.

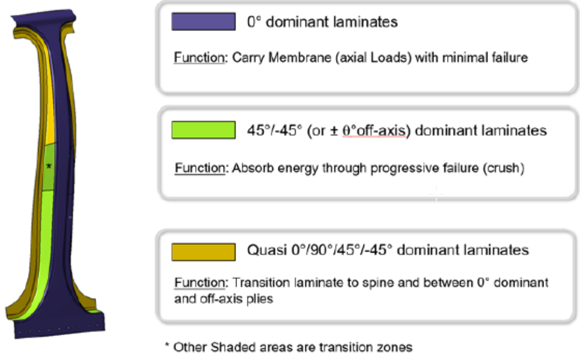

Figure 3. Hat Composite Design with Discrete Functionality.

Geometrical design of the composite B-pillar evolved during iterative design loops through feedback from finite element (FE) simulation of the crash event. The final “TAB” Design, shown in Figure 4, features cutouts in the Hat section. These cutouts significantly reduced strain concentrations in the Spine and also resulted in a composite design that was lighter and more manufacturable.

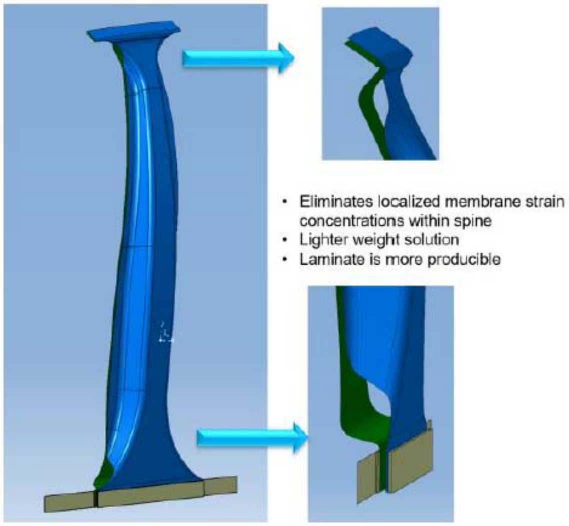

Figure 4. Finalized TAB Design.

CATIA Composites Engineering Design (CPE) and Composite Design for Manufacturing (CPM) provided process-oriented tools dedicated to the design of composites parts from preliminary to engineering detailed design to direct generation of manufacturing data. CPE offers three methods for composite definition that vary in function and complexity and robustness. For this effort, all composite components were defined using the Grid Based Method to capture and transition the discrete functionality within various regions within the structure.

Materials

Carbon fiber reinforced thermoplastics were chosen as candidate materials for the design, analysis, prototyping, test and evaluation of a B-pillar. An initial assessment was performed to evaluate material forms and thermoplastic resin combinations with potential for scalable manufacturing processes in the automotive industry.

A materials requirements document was created to source carbon fiber thermoplastic materials from suppliers in the composites industry, describing the fiber, resin and material form criteria for this effort. For down-selection of promising candidate systems for detailed assessment, a preliminary materials screening strategy was adopted for all materials sourced in this effort. The strategy centered on the measurement of three key mechanical properties:

- 0-degree tension for translation of fiber properties
- 90-degree tension for processed laminate quality and sizing or fiber-matrix adhesion
- ±45-degree tension for in-plane shear and ductility assessment

In addition to these tests, ultrasonic scans for panel quality, fiber volume fraction and density measurements were performed for all material systems.

Based on this screening procedure two material systems were down selected for the two regions of the B-pillar (Figure 5). Tencate PA6 / Hexcel AS4 12K was selected for the Hat section due to its superior shear elongation. Arkema Elium / T700 was selected for the Spine part because of its good tensile properties and advantages of good manufacturability and relatively low material cost.

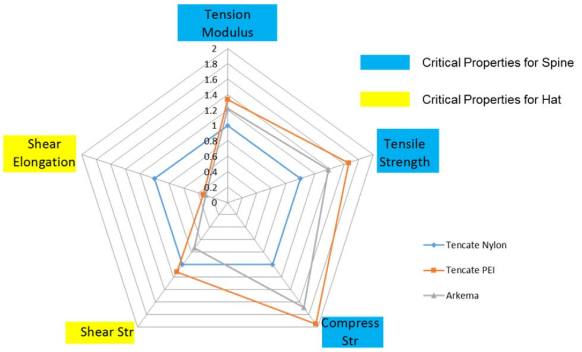

Figure 5. Relative Key Properties of Selected Material Systems.

Throughout the design of the composite B-pillar, these initial properties measured from quasi static coupon tests were complemented by more in depth analyses of material properties. As the B-pillar design evolved, additional coupon compression tests as well as a sub component test program, featuring quasi static crush tests of head section profiles, were carried out to measure the post damage behavior of the selected materials.

For bonding of the two B-pillar sections, Plexus MA530 adhesive was selected.

SMARTree software was used for material property management. The software assisted calculating different sets of nonlinear material data from test results as well as distributing them to the design team members.

Finite Element Modelling and Simulation

During the iterative design process, a large quantity of design variants of the composite B-pillar were evaluated for crash performance using dynamic, explicit FE simulation. To allow for quick evaluation of design changes and thus an efficient design process, the generation of the FE model was automated.

Altair Hypermesh was used to create an FE-Mesh based on the geometric shape derived from CATIA. The composite layup information is mapped onto this mesh and a subsequent draping analysis is performed within Hypermesh to obtain an accurate estimate of the ply angle for each ply and element. To covert the generated FE Model into the LS-Dyna format, an automated interface was implemented.

The FE simulations were carried out in LS-DYNA due to the variety of material models available for composites in this explicit FE code. In order to model the multi-layer composite laminates, layered shell elements were used. MAT54 was down-selected as the material model of choice for the composite B-pillar application offering a linear elastic behavior up to failure and a drop off to a limit value after failure. Although other material models in LS-Dyna offer nonlinear material behavior, the control over nonlinearity in these models is limited. Selection of MAT54 was considered a conservative approach. Throughout all project stages the available material data was used to calibrate the material models, thus leading to increasing prediction capabilities as the B-pillar design evolved. Starting with basic properties from material screening up to post failure damage behavior captured from sub component tests.

A non-congruent solid adhesive layer was modeled at all adhesive locations using *MAT_COHESIVE_MIXED_MODE element formulation in conjunction with tie constraints. The adhesive model was fitted to test data obtained from tension and lap-shear tests.

MANUFACTURE AND TESTING

To prove the validity of the documented design process and to demonstrate the feasibility of the developed B-pillar component five B-pillars were manufactured and tested by UD-CCM.

Manufacture

Due to the different material systems chosen for Spine and Hat section, production utilized different processing approaches. Both the liquid molding process for Spine production and the forming process for Hat manufacture have potential to be scalable for mass production. The mass production equivalent for the Spine vacuum infusion being a resin transfer molding process, which is well established for thermoset CFRP.

During **liquid composite molding (LCM) processing of the Spine** a dry fiber textile is impregnated with a liquid low-viscosity resin. The applied pressure gradient between the injection and vent gate allows resin infiltration of the fiber reinforcements.

Flat pattern of the preform design was generated and cut from uni-directional carbon fabric (Figure 6).

Figure 6. Preform Kitting.

An adhesive layer was added through a heat treatment to minimize any loss of individual tow bundles as the material was cut and handled. The final assembly was heat treated under vacuum at 120°C for an hour and resulted in a good dimensional stable preform which was further processed for final infusion.

Initial infusions showed significant void space close to the injection locations. The pressure in the injection gates at the end of infusion will drop to almost atmospheric pressure. It was speculated that this allows generation of vapors in the infusion areas resulting in an increase in vapor pressure pushing the resin out of the preform area locally. The effect led to the observed dry-spot development (Figure 7). In all further experiments, the injection ports were inverted to a vent as gelation in the resin bucket was observed. This minimized vapor generation and thus dry-spot development.

Figure 7. Dry-Spots after Infusion.

Over the project period 10 Spines were produced, with 5 being used for impact testing.

Hat Section Manufacturing: Forming of continuous uni-directional carbon fiber thermoplastic parts is still in its infancy with limited thermoplastic uni-directional prepreg material availability coupled with no established simulation tool to predict the forming process. The major processing challenge is the forming of the heated but still viscous blank material over the tool.

The three major processing steps include consolidation of an engineered blank and heating of the blank followed by forming of the blank in a die. The NHTSA program established a three-stage thermoforming system at UD-CCM which integrated a 54 kW infrared (IR) heater station, blank preparation station with a shuttle in a 150-ton press system (Figure 8). The system allowed placement of the blank into the shuttle, rapid heating of the blank under the IR heater followed by forming in the press section. The system was used to produce flat components for mechanical tests and small-scale Hat sections for sub-element testing. During full-scale Hat production, the engineered blank was heated in the press using convection and then pressed in shape.

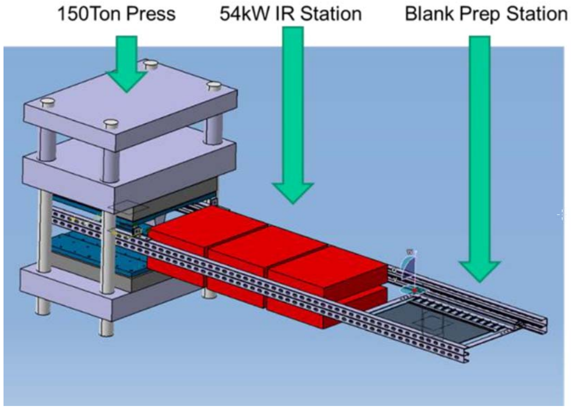

Figure 8. Schematic of Forming Station.

For production of the full-scale Hats, engineered blanks based on the final B-pillar design were assembled manually (Figure 9). Twenty-six prepreg layers were arranged to form the blank with the majority of the off-axis plies being located on the vertical walls of the Hat. Plies were manually cut using a pattern master and pieces were attached to the main body using a point welding process. The final blank was consolidated under vacuum.

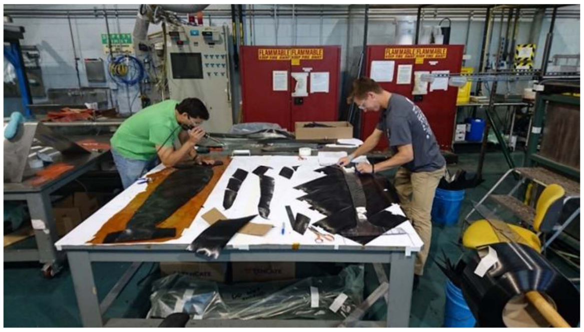

Figure 9. Assembly of Prepreg Pieces to Form Hat Blank.

The IR heating cell, shown in Figure 8, was extended to accommodate a larger blank but uniform heating was difficult to accomplish using the heater bank system. Heat gradient between individual heater units as well as temperature losses along the cell edges resulted in unacceptable temperature gradients of more than 10°C. Thus, the press and molds were insulated and the cavity was heated using the integrated press and external convection heaters. A blank was placed on the mold surface and the system was heated.
The stamping process was initiated at 230°C. After forming, the part was actively cooled to room-temperature. A total of six parts were manufactured successfully using this approach.

B-pillar Assembly was achieved by adhesively bonding Spine and Hat. Therefore the tool used to manufacture the Hat in the thermoforming process also served as a jig for assembly and bonding of the Hat to the Spine. After both Hat and Spine were fabricated by their respective processes and trimmed to final shape adhesive dispensing was performed with the UD-CCM robot (Figure 10).

Figure 10. B-pillar Assembly.

Testing

As final assessment of the composite B-pillar, a drop tower test was performed at UD-CCM.

The B-pillar test setup included a generic steel rocker to provide realistic boundary conditions for the B-pillar compared to the FMVSS No. 214 side impact crash test. Figure 11 shows the clamping fixture for the steel rocker as well as the complete assembly including the composite B-pillar, the generic steel rocker and the fixtures on either side of the rocker and on the top of the B-pillar. The top of the B-pillar was clamped directly in this drop tower setup. The steel rocker was a single use component and partially impacted and deformed during the drop tower tests.

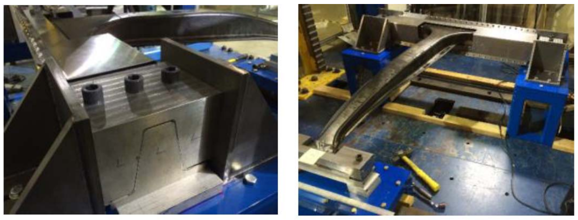

Figure 11. Drop Tower Setup.

The B-pillar was impacted by a rigid steel impactor which allowed for a small angular rotation around the vehicle x-axis. In previous FE analyses this configuration had been found to represent the FMVSS No. 214 loading conditions closely considering the limitations of a drop tower facility.

The tests were conducted at an impacting mass of 568.8 kg and an impact velocity of 7.26 m/s which yielded an impact energy of 15.02 kJ. During the tests impactor displacement as well as forces at the impactor were measured. Additionally the B-pillar deflection and strain field was measured on the far side of the B-pillar with a digital image correlation system. Additional force measurements were conducted at the B-pillar and rocker fixtures.

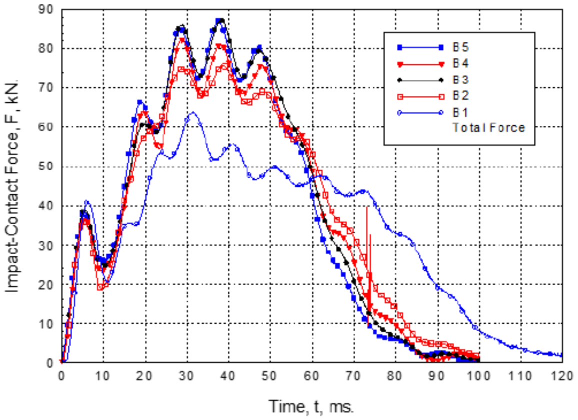

Figure 12. Time History of Impactor Force.

Experimental Results were used to judge the B-pillar performance as well as to validate the virtual prediction and the design process. Figure 12 shows time history of impact contact forces for all five experiments. Investigating the high-speed photography of the first test (TOP-LVI on B-pillar B1) revealed that the roof clamp fixture, although firmly bolted to the floor, slid inward towards the rocker during impact. Additional measures were taken such that sliding of the roof clamp fixture was prevented. The inadequate boundary conditions in the first test resulted in additional compliance, longer duration impulse loading and a reduction in the peak load. The validity and functionality of all other instrumentation was proven in this initial test.

Subsequent tests were compared to the FE simulation model prediction as shown in Figure 13. While force over time as well as deformation shape show very similar peak results and a good over all correlation between test results and model prediction, the impactor displacement is significantly higher in the test data. Since the B-pillar far side deflection obtained from the test is equal to the prediction, the difference in impactor displacement indicates a higher amount of B-pillar crushing taking place in the drop tower tests.

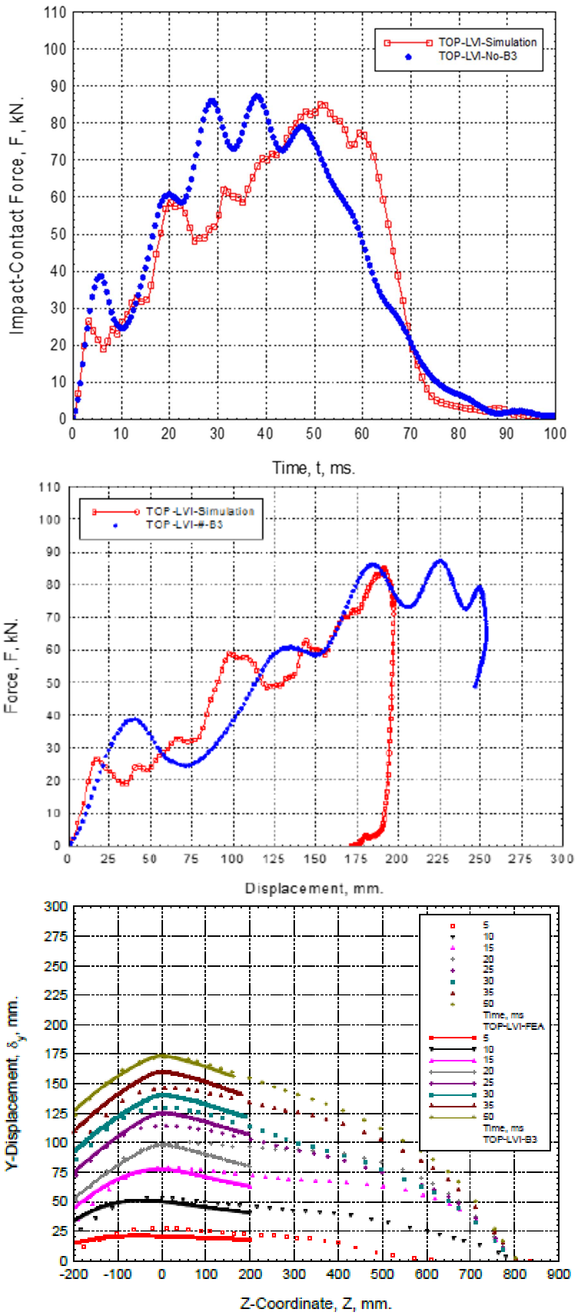

Figure 13. Comparison of FE Model (red / dotted) and Test Results (blue / solid).

To judge the performance of the B-pillar with respect to structural integrity after the impact, the specimens were thoroughly inspected visually. As predicted, the Hat section showed significant amounts of crushing and fiber damage as shown in Figure 14.

Figure 14. Crushing of Hat Section.

Figure 15 shows the adhesive bond between Hat and Spine which failed locally in the areas predicted by the simulation model.

Figure 15. Debonding of Hat and Spine.

The Spine did not show any fiber damage, though delamination in the Spine was visible at the rocker bonding location (Figure 16). However, a significant fraction of the Spine laminate was still adhesively connected to the rocker, which led to the B-pillar being able to arrest impactor movement after rebound and supporting the static load.

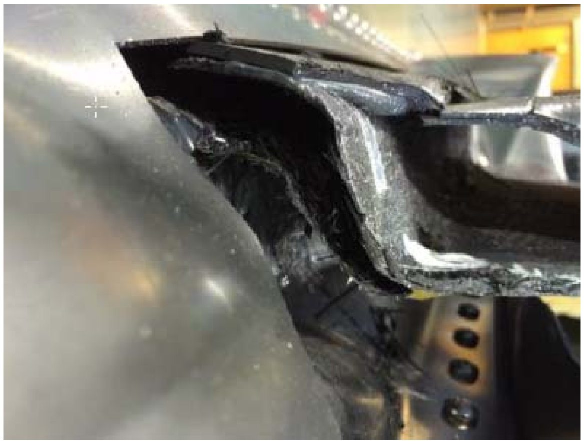

Figure 16. Spine Delamination.

CONCLUSIONS

UD-CMM and BMW investigated thermoplastic carbon fiber reinforced materials for vehicle side frame structures. The proposed B-pillar was designed to meet structural and crash safety requirements (e.g., FMVSS No. 214 barrier) using thermoplastic composites which offers significant advantages (e.g., recycling, joining) compared to thermoset with the potential for improved crash performance. Novel side-impact crash concepts maximizing crash performance have been developed and commercial available thermoplastic materials were characterized to define appropriate material models and to evaluate energy absorption mechanisms. Predictive engineering at all levels, from coupon to sub-element to full-scale, guided the material down-selection. The same CAE tools simulate full vehicle to component & test setup behavior and were used to optimize manufacturability and structural / crash performance. Sub-components and B-pillars were fabricated using stamp forming and infusion processes, allowing scalability with the potential to meet automotive production rates in the future. The UD-CCM high energy drop tower was used to validate the predictive engineering tools and crash performance of the proposed B-pillars under realistic side-impact crash conditions.

The B-pillar design was spatially optimized for energy absorption (ductility), stiffness, and strength while maintaining part producibility and vehicle integration. BMW established B-pillar performance metrics derived from full-vehicle crash simulations and other design and integration requirements. UD-CCM provided a full range of capabilities in materials selection and evaluation, composite design, analysis and crash simulations, process development and manufacturing (tooling, part production, trimming), full-scale pillar assembly and high-energy impact testing. This project has demonstrated design, materials, manufacturing and joining methods with continuous carbon fiber thermoplastics, at technology readiness level (TRL) 4-7 to meet automotive industry and government safety specifications.

Key achievements from this project are summarized as follows:

- Successful fabrication and manufacture of an all thermoplastic composite B-pillar that is 60% lighter than the existing metallic design while meeting project requirements for NHTSA FMVSS No. 214 side-impact crash.
- State-of-the-art CAE tools were evaluated (with internally developed data translation) simulating full vehicle to component impact (Dassault Systemes CATIA, Altair HyperWorks & LSTC LS-DYNA).
- Innovative production methods were developed and demonstrated for this multi-material part that included infusion and thermoforming tailored blanks with the potential to meet 2 minute cycle times.
- Adhesive bonding methods were developed and automated for dissimilar thermoplastics and steel interfaces.
- Automated trimming of the thermoplastic components was developed and demonstrated without damage to the composite structure.
- A test fixture was designed and integrated into UD-CCM high-energy impact tower simulating the crash behavior during side-impact crash without using a full vehicle structure.
- Multiple full-scale B-pillar assemblies (incorporating steel roof and frame rail) were successfully impact tested under 100% equivalent energy of FMVSS No. 214.
- The composite B-pillar response in the vehicle sub-component configuration satisfies all of the intrusion safety requirements to meet the requirements of FMVSS No. 214.
- All composite B-pillars exhibited rebound and post-impact structural integrity in terms of fully supporting the impactor dead weight of 568.80 kg.
- The impact test was simulated and compared to the experimental data (deflection, load, and others), validating the predictive engineering approach.

The goals of the project, validating the predictive engineering tools and demonstrating equal or better occupant safety performance at reduced weight as equivalent steel vehicle components, have been successfully accomplished.

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APPENDIX

Appendix 1. Larger depiction of Figure 1: Design Process for carbon composite component in vehicle crash application.