VALIDATION OF MATERIAL MODELS FOR CRASH TESTING OF CARBON FIBER COMPOSITES: OVERVIEW

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Abstract

The objective of this four-year, $7 million US Department of Energy (DOE) and the US Advanced Materials Partnership (USAMP) Cooperative Agreement project is to validate and assess the ability of physics-based material models to predict crash performance of primary load-carrying carbon fiber composite automotive structures. Models evaluated include Automotive Composites Consortium/USAMP-developed models from the University of Michigan (UM) and Northwestern University (NWU), as well as four major commercial crash codes: LS-DYNA, RADIOSS, PAM-CRASH, and Abaqus. Predictions are being compared to experimental results from quasi-static testing and dynamic crash testing of a lightweight carbon fiber composite front bumper and crush can (FBCC) system which was selected for demonstration via design, analysis, fabrication, and crash testing. The successful validation of these crash models will facilitate improved design of lightweight carbon fiber composites in automotive structures for mass reductions. This paper outlines the project, including the program objective, approach, and a summary the results to this point.

Program Overview

Background, Objectives and Approach

The objective of the Validation of Material Models (VMM) project is to validate the predictive capability of physics-based computational crash models for carbon fiber composites. This will enable broader use of the models in the design of automotive carbon fiber primary structural crash and energy management systems. Models considered include existing constitutive models in commercial codes, as well as models developed in projects jointly sponsored by the Automotive Composites Consortium (ACC) and the US Department of Energy (DOE). The models are assessed by comparing predictions of quasi-static and dynamic crash performance of a demonstration part with the actual results from testing. The component selected was a front-bumper/crush-can (FBCC) system, which is a key aspect of energy absorption in a frontal impact event. A gap analysis identifying the shortcomings of the modeling approaches will be the final deliverable of the project and will be conducted in late 2016. Successful validation of the material models will enable the design of light-weight, crashworthy automotive structures composed of production-feasible carbon fiber composites. The mass reductions from the carbon fiber structures is an enabler for improved fuel economy and reduced greenhouse gas emissions.

USAMP has collaborated extensively on research with academia, materials suppliers and engineering design software vendors to accelerate the development of advanced computational tools for simulating the crash response of composites and vehicle structures. Several new material models for predicting the behavior of carbon fiber composites were developed by academic collaborators over the last decade under the oversight of USAMP and ACC. Of these, two models in particular are promising enough to be used for crash simulation of composite structures: University of Michigan's Representative Unit Cell (RUC) based model and Northwestern University's Micro-Plane model. In addition, crash software developers have also developed many advanced constitutive models that are used to characterize the highly nonlinear crash response of composite structures in the four major commercial crash codes: i.e., LS-DYNA, RADIOSS, Abaqus and PAM-CRASH. These models require validation, which is the subject of this project.

A summary of the material characterization, design, and validation process flow is shown in Figure 1. Material models were built for each software code based on coupon test data for selected material systems, then calibrated and tuned at the element and coupon level. In addition, impact and bending tests were conducted on a simple structure with many features similar to the final FBCC (the "Hat Section Component"). Results from this testing were provided to the modelers to further tune the code. Tests were conducted on a steel FBCC from an existing vehicle to establish performance requirements. The carbon fiber FBCC was designed using existing predictive tools to absorb impact energy equivalent to the reference steel FBCC under various crash-loading modes. The designed FBCC was then fabricated, assembled, and tested in physical crash tests corresponding to six different modes. Test results were compared to predictions from the analytical tools to assess the accuracy of these tools.

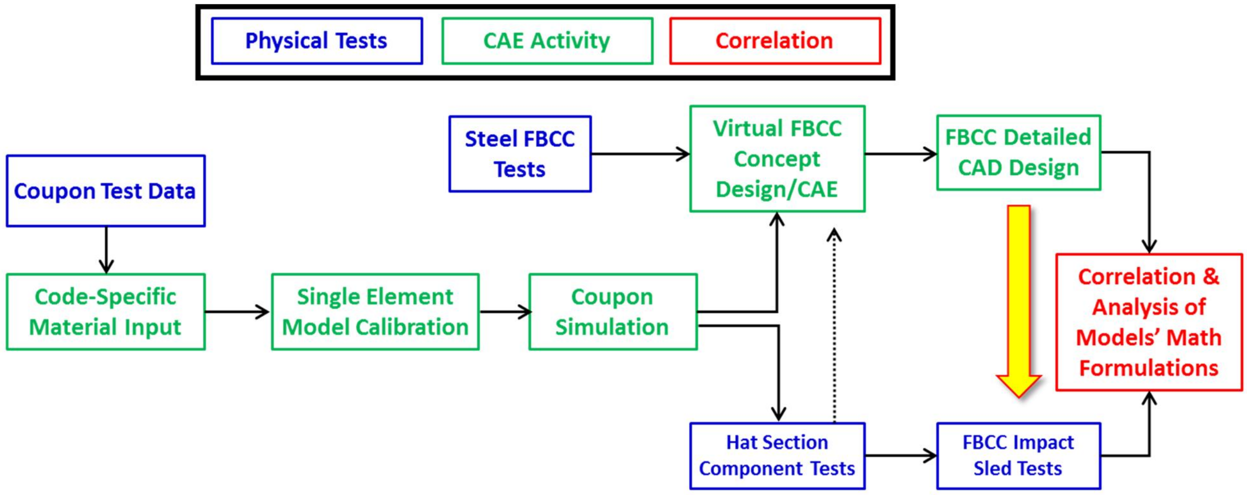


Figure 1: Material characterization, design, and validation process summary.

Project Organization

The project is organized into seven main tasks:

Task 1: Project Administration/Management

A DOE requirement is that Task 1 is the Project Administration and Management. Technical project management is provided by M-Tech International LLC, with accounting and other administrative services provided by Bucciero and Associates.

Task 2: Experimental/Analytical Characterization of Crash Testing of a Steel FBCC

In order to design a functional and representative FBCC, we needed to know the requirements of an FBCC in a current production vehicle. Thus, we selected the steel FBCC from a current mid-sized sedan, and impacted it on a crash sled in six load cases. From the results of these crash tests, we established the design targets for our composite FBCC.

Task 3: Design of a Composite FBCC

Using the results of Task 2 as design targets, we selected and characterized a material and process system, then designed a representative FBCC.

Task 4: Manufacture/Assembly Composite FBCC

Based on the Task 3 design, we procured tooling, molded bumper-beams and crush-cans, and developed assembly methodology to obtain a ready-to-crash FBCC.

Task 5: Crash Test Composite FBCC

Using the crash test methodologies from Task 2, we are crash testing and analyzing the composite FBCCs.

Task 6: Non-destructive Evaluation of Composite Structure

Non-destructive Evaluation (NDE) methods for the evaluation of this complex composite structure have been developed. In addition, possible methods for Structural Health Monitoring of the structure in-use are being investigated.

Task 7: Compare Experimental Results with Analytical Predictions

The payoff of the entire project: How well have we been able to use existing and experimental CAE models to predict the crash behavior of this carbon fiber composite?

Collaborators

This project was funded by the DOE Office of Vehicle Technology (DOE OVT), which provided continued oversight to make sure the project was on track to meet its goals and timing. It brought together a large number of participating organizations and individuals. Participating organizations and their primary roles are summarized below and in Figure 2.

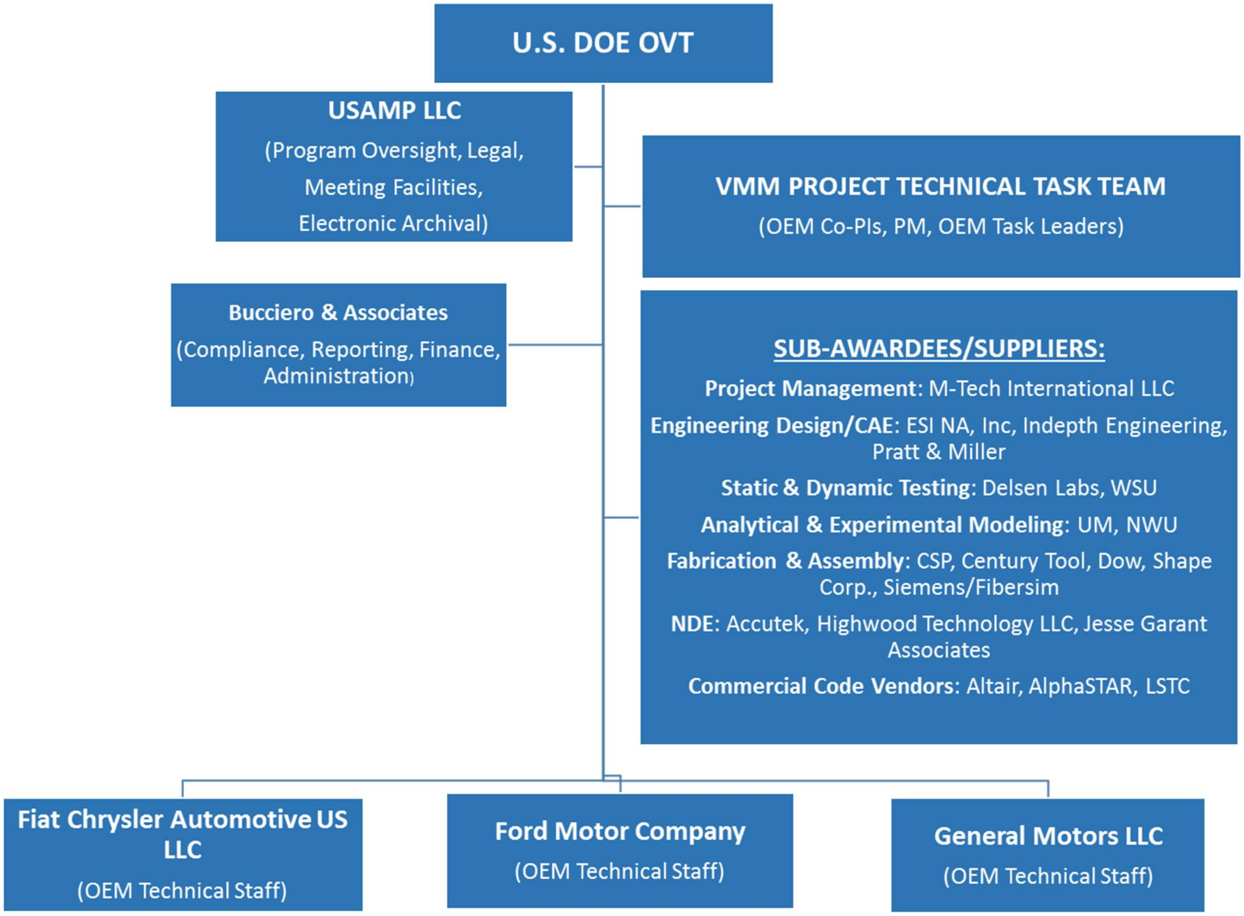


Figure 2: Organizational structure for the VMM project.

OEM industry collaborators:

- GM, Ford, and FCA collaborated through USAMP to co-direct and manage the project. In addition, much of the fabrication and testing was conducted in OEM-operated labs.

Academic collaborators include:

- Northwestern University: Prof. Zdenek Bazant has worked with ACC on the Micro-Plane RUC model. He and his team have predictively modeled the crush-cans for this project, to determine if their material model can be validated in an automotive crash scenario.
- University of Michigan: Prof. Tony Waas has worked with ACC on the Meso-Scale RUC model. He and his team have predictively modeled the crush-cans and bumper-beam for this project, to determine if their model can be validated in an automotive crash scenario.
- Wayne State: Prof. Golam Newaz and his team have provided the crash testing for the project, including instrumentation, equipment, protocols, fixturing, and crash analysis.

Non-OEM Industry collaborators include:

- M-Tech International: Provided technical project management for the project.
- ESI North America: ESI was the primary vendor for application of the commercial modeling

codes. They are responsible for the predictive analysis of the steel FBCC and lead the design and predictive analysis of the composite FBCC using the four commercial codes. All iterative conceptual design and CAE activity was performed in PAM-CRASH. ESI also provided analysis and forming simulations to recommend a manufacturable design for the FBCC, as well as identify potential problems in molding.

- Century Tool: Century was responsible for producing the complete set of compression molding tooling and ply-holding fixtures for the final FBCC components, as well as working closely with the fabrication supplier to conduct molding runs.
- Continental Structural Plastics: CSP was the major composite fabrication supplier and was responsible for fabrication of plaques, simple shapes for materials evaluation, and the composite FBCC.
- Highwood Technology: Highwood Technology was responsible for the development of NDE for the carbon fiber composites.
- Dow Automotive: Dow was responsible for joining process development and final assembly of the thermoset composite FBCC.
- Shape Corporation: Shape is responsible for fabricating the thermoplastic crush-cans for crash testing.
- Livermore Software Technology Corporation: LSTC is calibrating LS-DYNA models with VMM material data to deliver custom material cards for CAE of the FBCC
- Altair Engineering: Altair is calibrating RADIOSS models with VMM material data to deliver custom material cards for CAE of the FBCC
- AlphaSTAR Corporation: AlphaSTAR is calibrating GENOA-based multi-scale models with VMM material data to deliver custom material cards for CAE of the FBCC.
- Siemens/Fibersim: Fibersim was used as the primary code to analyze ply orientation and optimize prepreg patterns for manufacturability evaluations.

Task Summaries and Major Achievements

Task 1: Project Administration/Management

A vertically-integrated research team of over 50 members was organized under USAMP (wholly owned by United States Council for Automotive Research LLC), comprised of over 25 technical staff from the USCAR Member companies: Fiat Chrysler Automotive US, LLC (FCA), Ford Motor Company (Ford) and General Motors LLC (GM) – collectively, the OEMs. The VMM project team includes another 25 representatives of supplier groups including leading academic researchers, automotive design/engineering service suppliers, composite manufacturers, NDE suppliers and crash test researchers.

The seven VMM Project technical and management tasks are being coordinated by M-Tech International LLC, a research and technology management organization, with program contracts administered by Bucciero and Associates, P.C. M-Tech worked with the two USAMP Co-PIs to conduct monthly technical task reviews and engaged the project's four OEM-based task leaders to anticipate technical and program risks, and develop proactive strategies to achieve key milestones and project outcomes.

Task 2: Experimental/Analytical Characterization of Crash Testing of a Steel FBCC

Testing of a steel FBCC system was used to develop test protocols and determine performance benchmarks used to evaluate the carbon fiber system. See companion report "*Validation of Material Models: Physical Crash Testing of Composite Bumper-Beams*" for further details on the crash test methods and results.[1] Specifically, acceleration, force, deformation time histories, as well as force-displacement curves were used to develop design requirements. Beams were tested in six crash modes: full frontal at 35 mph, 40% offset at 30 mph, 30° angular at 20 mph, and center pole impact at 20 mph. Low speed damageability tests were also conducted at 10 mph at center and quarter impact. See Figure 3 and Figure 4 for schematics of these modes. In addition, these tests were used as a baseline to determine the accuracy of the commercial crash software models (PAM-CRASH, LS-DYNA, Abaqus and RADIOSS) for predicting each crash mode.

For all test modes, a sled-on-sled setup was employed (Figure 5). The following measurements were recorded to use in comparing crash model predictions: accelerations using accelerometers, force using the accelerometers and load cells, overall system displacement using high-speed video analysis and accelerometers, and crush-can deformation using potentiometers and high-speed video analysis. A sample testing result for full frontal impact is shown in Figure 6, showing good repeatability. Steel beams absorb energy through plastic deformation by folding upon itself. For full frontal, average crush force was approximately 225 kN and crush distance was 175 mm.

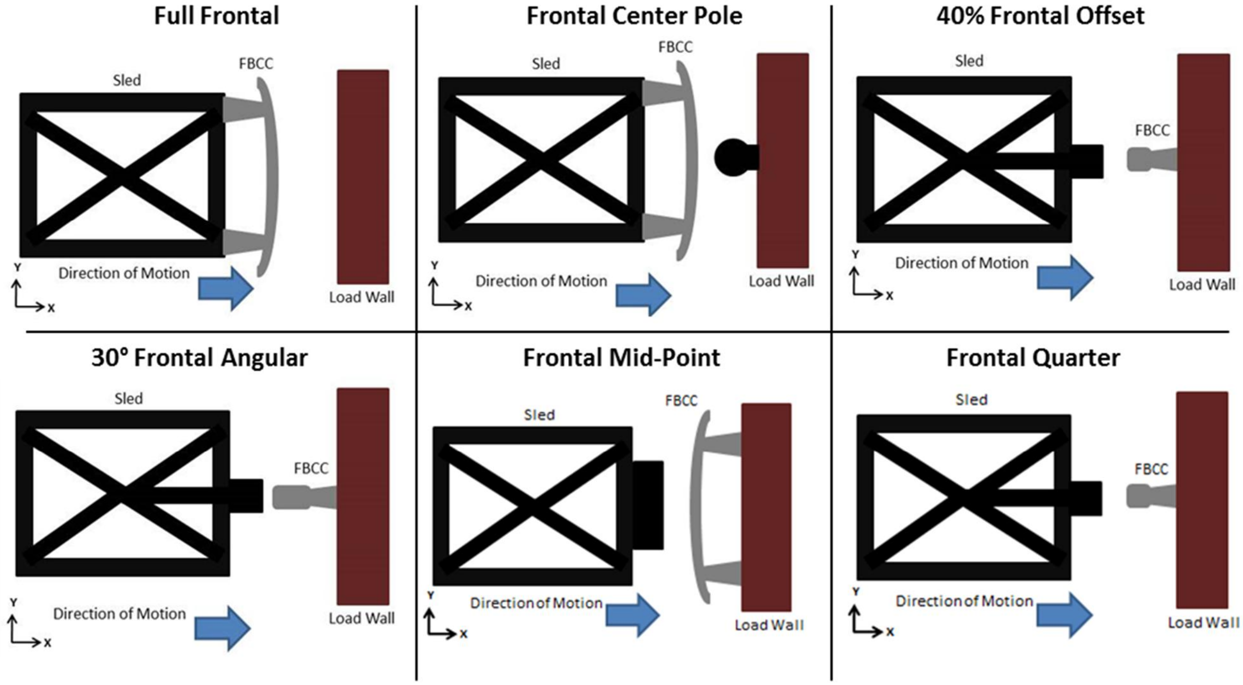


Figure 3: Top view of the six crash modes tested.

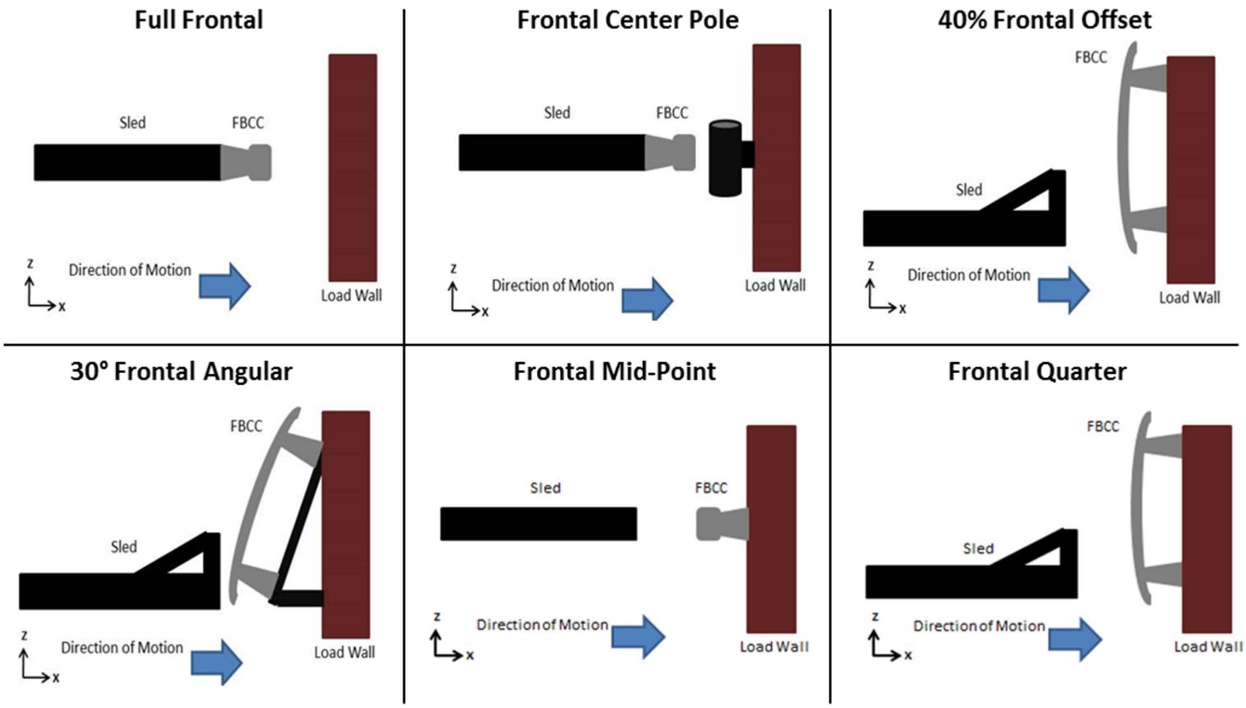


Figure 4: Side view of the six crash modes tested.

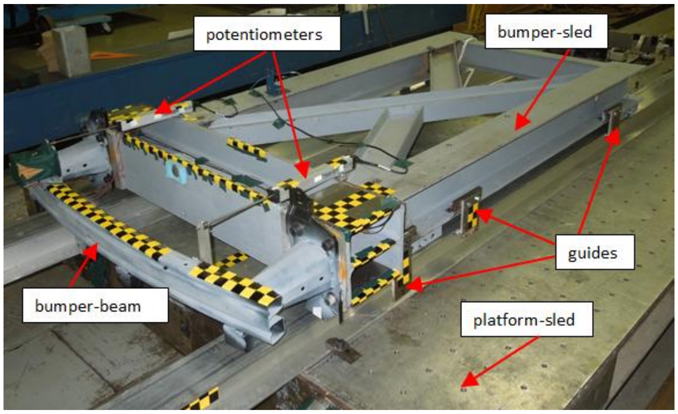


Figure 5: Set-up of sled-on-sled system used for all high-speed test modes.

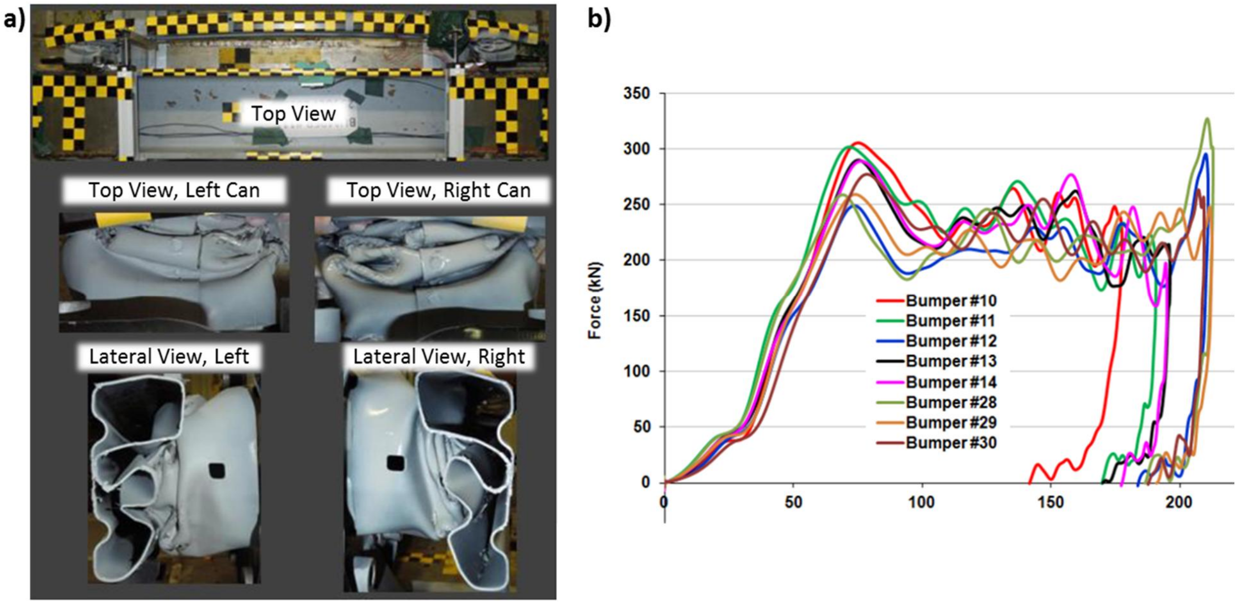


Figure 6: Samples crash results for full frontal testing of the steel FBCC, including a) photographs of a beam following a test, and b) force vs displacement for all the beams tested.

Task 3: Design of a Composite FBCC

Task 3.1: Material and Process Selection

While this is a research effort and not directly intended at production of a commercial automotive subsystem, it is important to ensure that we are studying materials and processes that could be used in volume automotive production. In particular, a pathway towards rapid processing was a key consideration. We selected compression molding of prepreg for the primary structural elements because it enables production of a high performance composite in a relatively short cycle time and with minimal investment in specialized equipment. See companion report "*Validation of Material Models: Thermoset Composite Materials and Processing for a Composite Bumper-Beam System*" for further details on the material selection and part manufacturing processes for thermoset systems.[2] The prepreg chosen was composed of standard modulus carbon fiber and an epoxy resin. Both unidirectional and woven prepregs were considered. Sheet molding compound (SMC) was co-molded with the prepreg to produce complex geometries, including the ribs of the bumper-beam and rear flanges of the crush-cans. The sheet molding compound used was composed of 1-inch randomly oriented carbon fibers and a vinyl ester resin.

Layup of the prepreg was also an important factor to consider to obtain the maximum crash performance. Several tests were used to compare some various layups. Standard coupon tests were used to compare the tensile, compression, shear, and flexural performance of various layups of prepreg molded as flat plaques. Impact and flexure testing of a simple structure, a closed-hat section, was used to assess the moldability of the layups and their performance under loads more similar to those experienced within the actual FBCC. Figure 7 shows images of a crush tube made by bonding a portion of the hat section to a flat plate, before and after an impact test. Results for three layups examined are given in Table 1. The three layups were: "Woven 0/90" with $[0/90/0/90/0/90_{1/2}]_s$, "Woven QI" with $[0/90/45/-45/0/90_{1/2}]_s$, and "Uni/Woven QI Mix" $[0/0/0/90/45/90_{1/2}]_s$. In the Uni/Woven QI Mix layup, layers 1, 2, 5, 10, and 11 were unidirectional fiber, while the rest were woven. Ultimately, a layup composed of only woven prepreg in a quasi-isotropic configuration was chosen for its superior performance in impact and good performance relative to the other layups in other tests performed.

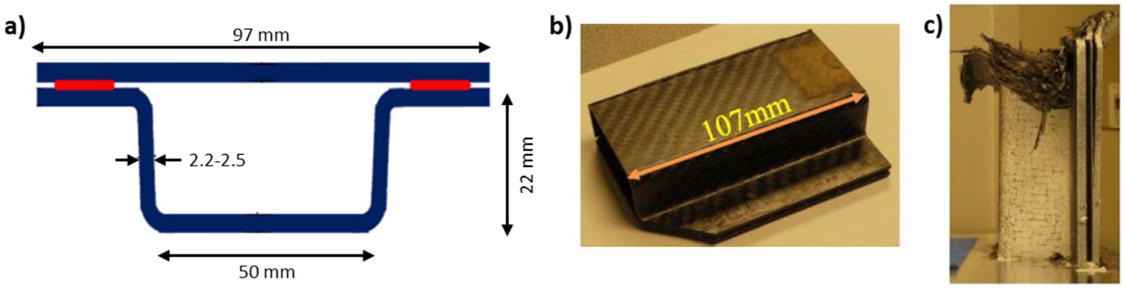


Figure 7: Images of the hat section bonded to a flat plate, including a) cross-sectional dimensions, b) a photograph of the structure ready for drop tower testing, and c) the structure after drop tower testing.

Table 1: Summary of results for the three layup in the drop tower test. The structures were impacted with a 74.5 kg mass dropped from the indicated height.

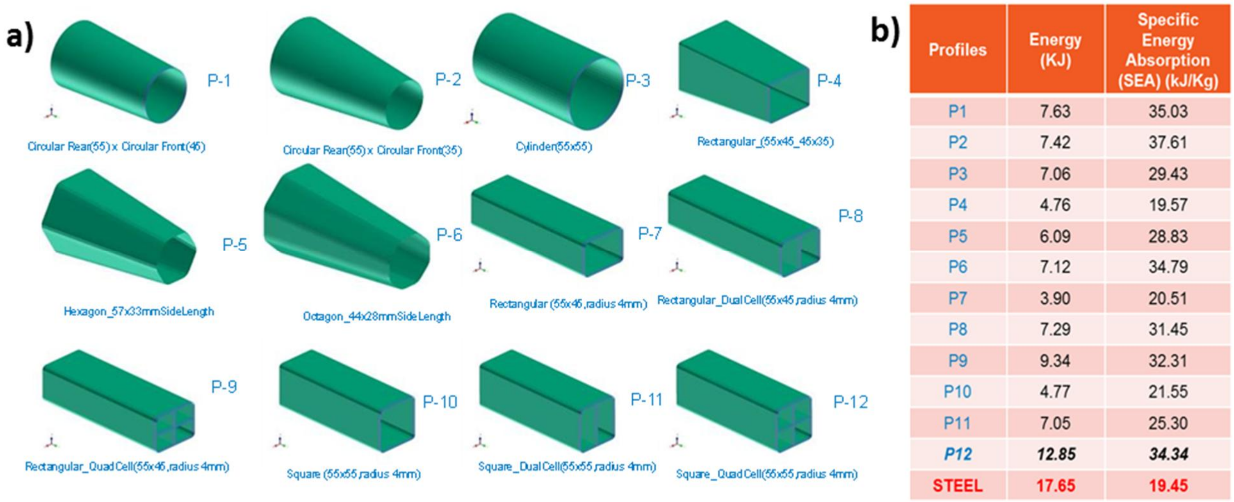
	Woven QI		Woven 0/90		Uni/Woven QI Mix	
Drop Height [m]	0.98	0.98	1.00	1.00	0.97	1.00
Crush Distance [mm]	18.2	15.5	16.2	17.7	20.1	16.3
Plateau Load [kN]	41	41	-	36	35	35

Task 3.2: Design/CAE Analysis of Composite FBCC

Many design concepts were generated and evaluated using PAM-CRASH to compare their crash performance based on simulations. See companion report "*Validation of Material Models: Design of a Composite Bumper-Beam and Assessment of Current Composite Crash Simulation Capabilities*" for further details on the design process for the FBCC.[3] In order to meet the steel FBCC performance, it was decided that the composite crush-can should have similar energy absorption and a progressive crush mode (front to rear). Material and process selection was an integral part of the design process. Several mechanical tests were conducted to aid in component design and to calibrate the model, including monotonic coupon testing (tension, compression, shear, fracture, etc.), cyclic loading, closed-hat section testing in bending and impact, and size-effect testing.

Figure 8 shows 12 different sections that were evaluated via CAE for the energy absorption, crush mode, and average load. Ultimately, a structure similar to P-5 was selected. This structure had relatively good energy absorption, had a tapered design that allowed for not using a crush initiator to ensure crush started at the impacted side of the can (narrower end), and flat facets to assist in achieving better NDE. Several front-bumper and FBCC concepts were also evaluated (Figure 9). After evaluation of the manufacturing requirements and design feasibility against the functional objectives of a bumper-beam, the team decided to pursue Concept 3. This design employs a compression molded, continuous fiber C-Section beam, with chopped, random carbon fiber SMC ribs. The ribs allow for final tuning and optimization of the crush, strength, and elastic characteristics of the bumper-beam for the different impact modes, and also aid in locating the cans for assembly and crush-can joining to the beam.

The final FBCC is composed of five parts, including the beam and the two crush-cans. The crush-cans are each composed of one “A” and one “B” part (Figure 10). The crush-cans are designed as two halves of a tapered cylinder, each with six flat facets, which are joined using flanges. The beam is swept and uses ribs for additional strength and stiffness. The components of the FBCC are joined using adhesive bonding. In addition, rivets are used on the crush-can flanges to improve bonding and act as peel stoppers. The FBCC is mounted to the vehicle using four bolt holes in the large flanges on the vehicle side of the crush-cans. In the event of a frontal crash, the crush-cans are the main energy absorbers and do so by progressive crush of the composite. By design, crush starts at the impacted-end of the crush-can and progresses towards the vehicle-end. Energy is absorbed through many delaminations, micro-cracks, fiber fractures, and other damages that are generated during this dynamic loading event.



Profiles	Energy (KJ)	Specific Energy Absorption (SEA) (kJ/Kg)
P1	7.63	35.03
P2	7.42	37.61
P3	7.06	29.43
P4	4.76	19.57
P5	6.09	28.83
P6	7.12	34.79
P7	3.90	20.51
P8	7.29	31.45
P9	9.34	32.31
P10	4.77	21.55
P11	7.05	25.30
P12	***12.85***	***34.34***
STEEL	**17.65**	**19.45**

Figure 8: Early composite crush-can design candidates and the predicted energy absorption in straight-on frontal crash.

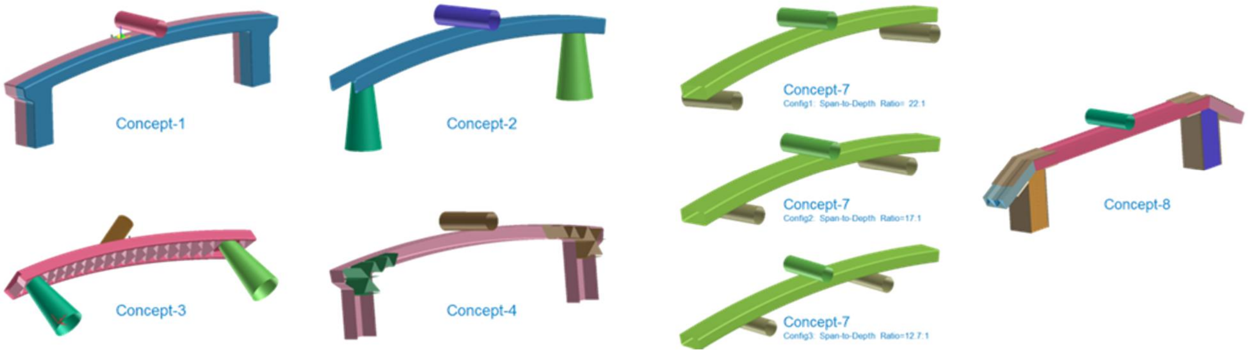


Figure 9: Early composite beam concepts that were evaluated.

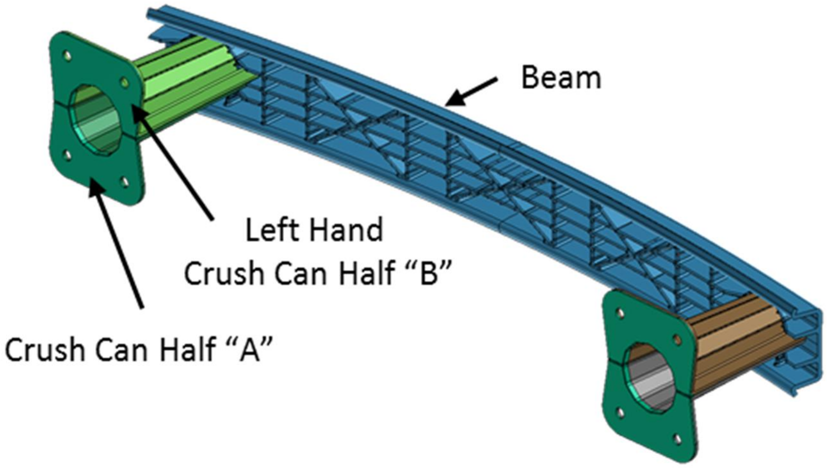


Figure 10: CAD model showing the structure of the FBCC.

Task 4: Manufacture/Assembly Composite FBCC

A total of 50 FBCCs were produced for testing, with three used for development of non-destructive evaluation (NDE) techniques and the rest for crash testing (Figure 11a). See companion report "*Validation of Material Models: Thermoset Composite Materials and Processing for a Composite Bumper-Beam System*" for further details on the material selection and part manufacturing processes for thermoset systems.[4] FBCC components were produced by compression molding using two-part tools. A total of three molds were required, including one of the bumper-beam, one for part "A" of the crush-can and one for part "B". All components were composed of a combination of sheet molding compound (SMC) and continuous-fiber prepreg, co-molded and co-cured (Figure 11b). This approach allowed for the use of the high performance prepreg in the main structural portions of the FBCC and the use of SMC to form complex structural features, including the beam ribs and crush-can flanges. The prepreg was precision cut using an automated cutting table, while the SMC was cut to shape by hand and the quantity was verified by mass. Prior to molding, the prepreg was manually preformed into rough 3D then preformed to shape using dedicated forming tools and stored in a freezer on a buck until it was time to mold. See companion report "*Validation of Material Models: Composite Fabric Manufacturing Studies by Simulation and Experiment*" for further details on the preform design process.[5] During molding, the parts were placed in the hot mold, cured, and removed. Following molding, the parts were trimmed to final dimensions using CNC milling. Parts were then joined using adhesive bonding and rivets. See companion report "*Validation of Material Models: Joining and Assembly System for Thermoset & Thermoplastic Composite Materials*" for further details on the FBCC joining and assembly. [6] Figure 12 shows the progression of the crush-can manufacture.

Several issues were identified during manufacturing of the FBCCs, including excessive resin runoff during molding, wear and distortion of the aluminum tooling, and defects identified by NDE. Corrections were made for these issues as feasible. NDE of the components identified several types of manufacturing defects, including fabric wrinkling, bunching, and stretching, which correlated with the reduced material properties. This highlights the importance of considering composite manufacturing when developing material models in order to capture locational variation in material properties that may occur near challenging geometries.

In addition to molding of thermoset-based parts, work was completed on manufacturing of thermoplastic crush-cans. See companion report "*Validation of Material Models: Development of Carbon Fiber Reinforced Thermoplastic Composites for a Front-Bumper Crush-Can System*" for further details on the material selection and part manufacturing processes for thermoplastic systems. Thermoplastics have the potential to absorb more energy than thermosets because of their generally higher fracture toughness. The crush-cans were composed of continuous carbon fiber/nylon prepreg for the main structural areas and chopped carbon fiber/nylon prepreg to take the place of the SMC. Woven and non-crimped fabric (NCF) continuous prepreg were compared. Manufacturing of the thermoplastic crush-cans followed a similar procedure to that of the thermosets. However, for the molding step some changes were required. The prepreg was preheated in a radiant oven to 260-315° C, then placed in the mold, which was maintained at 140° C. The mold was then closed and the prepreg took shape and hardened very rapidly and was removed. Crash testing of these components is pending and will be complete during the second quarter of 2016.

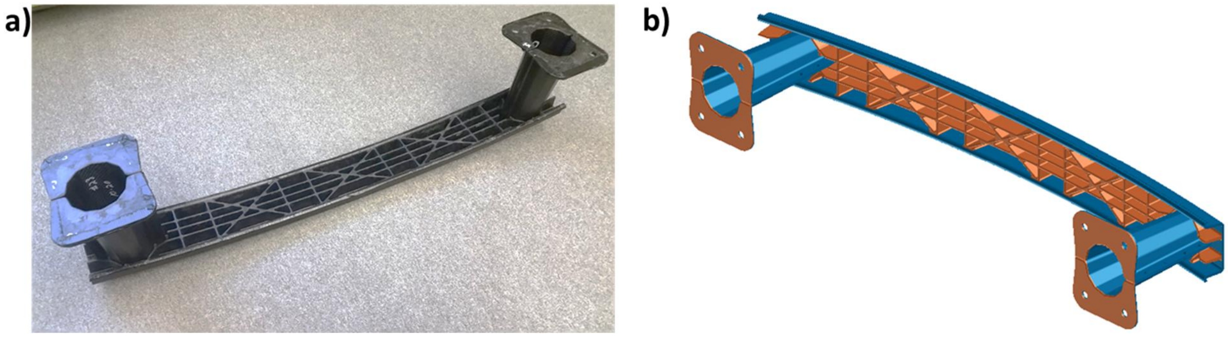


Figure 11: a) Image of an assembled FBCC. b) Model of the FBCC showing the prepreg components in blue and the SMC components in orange.

Figure 12: Manufacture of a thermoset crush-can from preforming to joining.

Task 5: Crash Test Composite FBCC

Crash testing of the composite FBCC will be completed for the same six modes that were tested for the steel beam. At the time of writing this report, test results were not available to be made public because CAE predictions are still in progress. Results will be discussed in the presentation and in future reports.

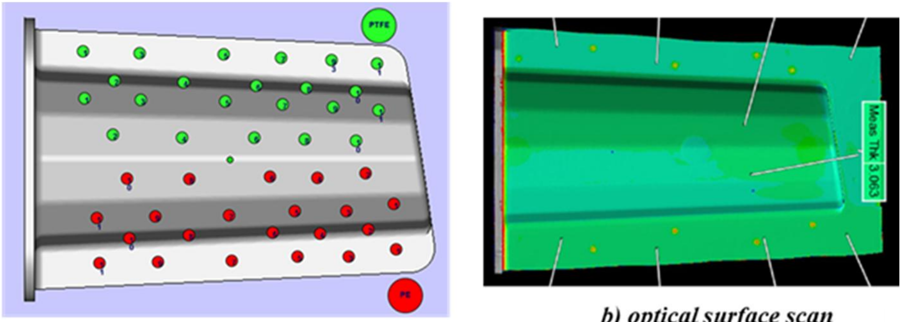
Task 6: Non-Destructive Evaluation of Composite Structure

The NDE team was tasked with the development of practical methods that can verify the build of the carbon fiber composite materials and assemblies. See companion report "*Validation of Material Models: Non-destructive Testing Throughout the Development of a Carbon-Fiber Composite Automotive Front-Bumper/Crash-Can Structure*" for further details on the development of NDE methods for composite automotive systems.[7] NDE is critical to ensure the quality of carbon fiber composites in safety-critical parts, such as an FBCC assembly. Safety-critical, automotive components are typically 100% NDE inspected. There is also a major concern with in-service monitoring due to the brittle nature of carbon fiber composites. Automotive components tend to be highly 3-dimensional, fairly small, and produced at high rates when in mass-production compared to parts for aerospace or wind energy. NDE methods were selected to both address these features and remain consistent with methods already widely used in the automotive environment. The four NDE methods selected were: 1) conventional x-ray radiography, 2) computed tomography (CT), 3) optical surface scanning and 4) ultrasonic pulse/echo using a linear phased array (UT-PA).

NDE methods were first evaluated on flat panels and the previously described hat-section. Two of the most important tasks in NDE development are to determine the type and size of discrepancies that significantly reduce the material strength. The primary discrepancies observed for the prepreg-based continuous fiber composites were delaminations and foreign matter contamination. Compression-after-impact testing indicated a critical flaw size of 6 mm in diameter in twill-woven prepregs with a quasi-isotropic layup.

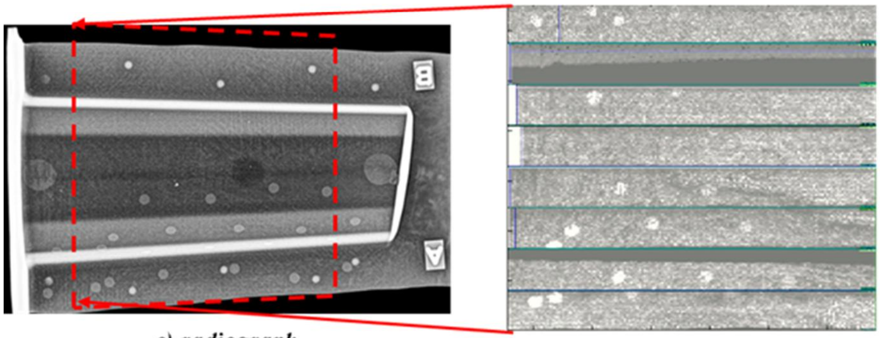
The crush-can and bumper-beam inspections presented significant NDE challenges. A comparison of the methods on the crush-can is shown in Figure 13. The radiography and CT required relatively low x-ray energies (20-100 keV) to match the low attenuation of the 3- and 6-mm thick components. CT has the additional difficulty of having a trade-off between the resolution and inspection volume. Usually these methods cannot find delaminations in thin sheets, although both porosity and delaminations were detected in the ribs of the beam. Ultrasonic pulse/echo was selected as the primary method to detect delaminations. Ultrasonic pulse/echo methods typically require careful alignment of the beam to be normal to the surface. To deal with this, the crush-cans were designed to have flat facets rather than a conical surface. This "design for inspection" was very beneficial and allowed careful inspection of the crush-can sides. On flat panels, ultrasonic pulse/echo was able to detect very small delaminations, image defects in 3-dimensions, and even determine ply orientation-angles. A linear ultrasonic phased array was used for both the crush-can and bumper-beam. However, the front-bumper was too thick to fully inspect at frequencies that would allow ply information.

To determine if the selected NDE methods had adequate sensitivity, thin 6-mm diameter inserts were molded into a crush-can and a bumper. Figure 13 shows the results for a crush-can with both polyethylene (PE) and polytetrafluoroethylene (PTFE) inserts. Ultrasound readily detected both insert types, at least up to 2-mm deep. Radiography detected all the PTFE inserts, but not the low-density PE inserts. The optical scans do no detect the inserts, as expected, but show uniform thickness and <0.2 mm deviations from the CAD models.



a) insert layout

b) optical surface scan



c) radiograph

d) ultrasonic C-scan

Figure 13: Detection sensitivity of a crush-can half using thin PE and PTFE inserts. a) Schematic of intended insert locations, b) optical surface scan of thickness, c) low-energy radiograph showing PTFE inserts, and d) high-frequency ultrasonic scan of PE and PTFE inserts.

Task 7: Compare Experimental Results with Analytical Predictions

This task has not begun at the time of writing this report. The results of the physical testing of the carbon-fiber composite FBCC will be compared with the CAE predictions and design targets to determine equivalency of performance. At least eight (8) different equivalency assessments are planned. The crash response predictions from the commercial codes and the ACC-developed academic material models will be compared to the physical test results. This will establish the predictive capabilities of these models. All analytical model predictions will be compared with each other, to determine the relative utility of these models, identify key gaps in predictive values and recommend best practices for application of each model.

Summary

The purpose of this project is to validate and assess material models used to predict crash performance of automotive structures for energy absorption during crash events. The goal is to enable more widespread use of carbon fiber composite structures in automotive vehicles for additional mass reduction to facilitate improved fuel economy and reduced greenhouse gas emissions. Crash tests on a production steel front-bumper/crush-can system were used to establish performance standards for the design of the composite system. A new carbon fiber FBCC system was designed for this project. Materials and production processes were selected to achieve excellent energy absorption with low mass and the potential for rapid production rates. Over 50 thermoset FBCCs were produced for testing, which is scheduled for completion during the second quarter of 2016. The FBCCs will be tested in six crash modes and compared to predictions from the commercial and academic models. NDE methods were evaluated and further developed for analysis of the composite FBCC. NDE methods are particularly important for this safety critical system to detect defects and ensure the system performs as designed.

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