

# VALIDATION OF MATERIAL MODELS FOR CRASH SIMULATION OF AUTOMOTIVE CARBON FIBER COMPOSITE STRUCTURES: PROJECT CONCLUSIONS AND KEY LEARNINGS

Anthony Coppola  
*General Motors*

Omar Faruque  
Derek Board  
Martin Jones  
*Ford Motor Company*

Jian Tao  
James Truskin  
*FCA US LLC*

Yijung Chen  
*Optimal CAE, Inc.*

Manish Mehta  
*M-Tech International LLC*

## Abstract

A final project overview and discussion of key findings is provided for this five-year Department of Energy (DOE) and the US Advanced Materials Partnership (USAMP) Cooperative Agreement project DE-EE-0005661, the objective of which was to validate and assess the ability of physics-based material models to predict crash performance of automotive primary load-carrying carbon fiber composite structures. The project concluded in March 2017, and this paper serves as a report-out on the findings of this research to the greater composites community.

## Background, Objectives and Approach

The Validation of Material Models (VMM) project sought to assess the predictive capability of physics-based computational crash models for carbon fiber composites for automotive applications. The overall goal was to increase the adoption of carbon fiber composite materials in automotive components through improved confidence in our ability to use these predictive tools for design and engineering of the system to meet progressive crush and safety requirements via vehicle lightweighting solutions. Material models considered included existing constitutive models in commercial codes, as well as models developed in previous projects jointly sponsored by the Automotive Composites Consortium (ACC, a division of USAMP) and the US Department of Energy (DOE). Finite-element analysis (FEA) models in commercial software suites for computer-aided engineering analysis (CAE) evaluated by the VMM project included:

- VPS (formerly called PAM-CRASH) from ESI Group
- LS-DYNA from Livermore Software Technology Corporation
- RADIOSS from Altair Engineering

- Abaqus from Dassault Systèmes
- GENOA-MCQ from AlphaSTAR Corporation

Predictions were obtained in each listed software from at least one modeling team comprised of either the original code developer/vendor, and/or engineering design/analysis service vendors serving the automotive industry. In addition, two separate sets of predictions were obtained from separate modeling teams (code developer and product designer) in two of the codes.

The results and discussion of performance by these codes are anonymized in this paper to ensure that the focus is on evaluating the accuracy of the CAE industry leaders as a whole, rather than a head-to-head competition to find the best software. Academic models considered included meso-scale Representative Unit Cell (RUC) models developed by the University of Michigan and Northwestern University. However, this paper will focus only on the predictive results obtained from the commercial codes.

CAE predictions were compared with experimental results from quasi-static testing and dynamic crash testing of a thermoset carbon fiber composite front-bumper and crush-can (FBCC) system gathered under multiple loading conditions. The FBCC design was developed using baseline experimental results obtained from testing a production steel FBCC tested in the same crash modes, and a goal of 30-35% mass reduction was set by USAMP OEM team for the composite design, aiming for equivalent energy absorption as the steel component. It was not the project's objective to directly compare performance of steel versus composite FBCCs. Importantly, composite material systems and manufacturing processes for the FBCC were selected based on technology maturity and suitability for application in mass produced future automotive systems to ensure relevance of the results. Virtual simulation was used early in the program to help ensure the final FBCC design met performance requirements.

The technical approach to the program is summarized in Figure 1. Modelers generating predictions were given the results from coupon testing, as well as component tests on a hat-section made using the same materials and manufacturing approaches. All modelers were given the same FBCC meshes and boundary conditions and asked to generate the material models based on industry best-practices. Modelers were given the freedom to select the most appropriate material model in their software for the problem. Critically, all composite FBCC predictions were generated blind of the actual crash test results to ensure true "predictions". Steel FBCC test results were shared with the modelers but were primarily used to establish performance criteria for the virtual design of the composite FBCC.

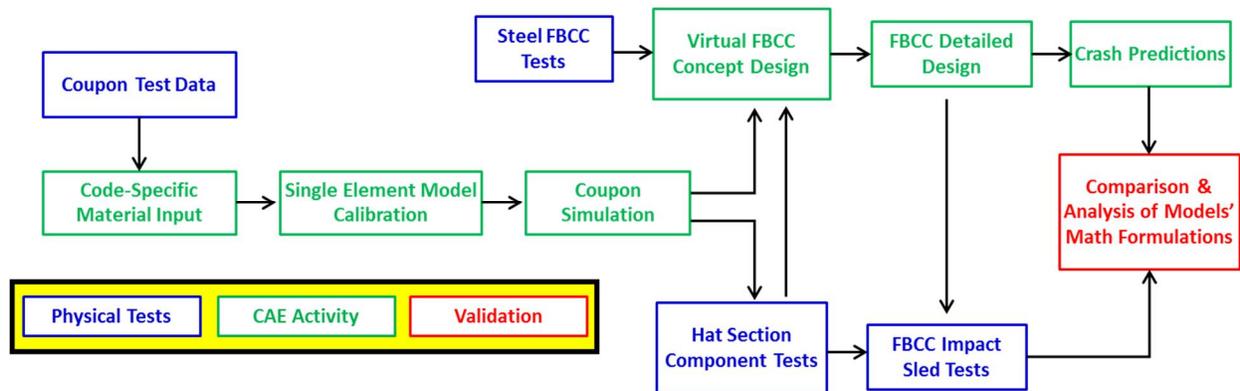


Figure 1: Material characterization, design, and validation process summary.

The focus of this paper is on comparison of the CAE predictions to the experimental results obtained in each crash mode, as well as conducting an analysis of the technological gaps identified by the VMM team in the modeling approaches that may have led to inaccuracies in the simulations. Towards this gap analysis, we looked at the influence of material characterization, component design, material selection, joining, manufacturing, and criticality of defects on the accuracy of the CAE predictions when compared to the experimental results. Many of the early results from this program were summarized in a series of presentations at the SPE-ACCE 2016 conference, and the reader is encouraged to reference those papers/presentations for more information [1-8].

## FBCC Design, Manufacture, and Crash Test Summary

### FBCC Design Overview

The FBCC is an assembled sub-system for crash energy management, comprised of five parts, including the bumper beam and the right- and left- hand side crush cans, which are each composed of one “A” and one “B” half (Figure 2). The crush cans are designed as two halves of a tapered cylinder that are assembled and joined using flanges. The bumper beam is swept and incorporates 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 peels 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.

The FBCC was designed to have equivalent energy absorption to the steel design, based on the steel design’s baseline crash testing, with a mass reduction of 30-35%. Iterative virtual design of the FBCC was performed in PAM-CRASH based on material models developed using coupon test data, as well as drop tower and four-point bend tests conducted on a composite hat-section manufactured using the same materials as the FBCC. These hat-section tests were used to tune the material models used in the virtual design.

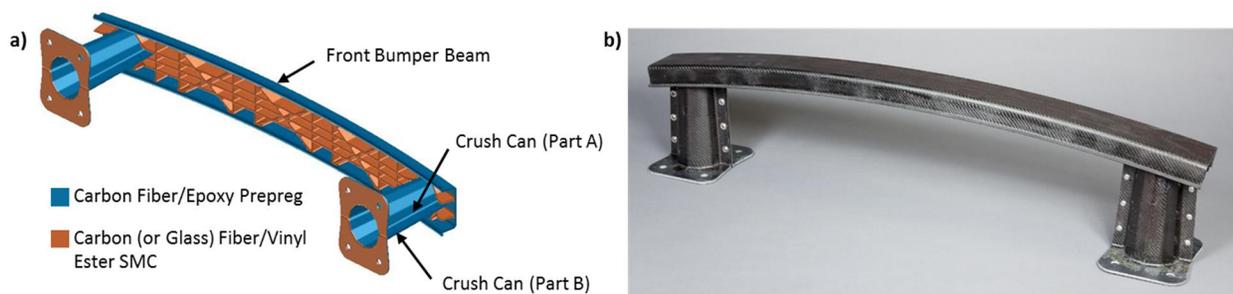


Figure 2: a) CAD image of the FBCC system. b) Photograph of an assembled FBCC used for crash testing.

### Materials, Manufacture, and Defect Analysis

Three material systems were used for fabrication of thermoset FBCC components. The first was a woven carbon fiber/epoxy prepreg, which was used for the primary structural features of the FBCC (shown blue in Figure 2). The prepreg was composed of 2 x 2 twill-woven Toray standard modulus carbon fiber with Cytec MTM 54FRB epoxy resin. The fabric was 343 grams per square meter with 58% fiber by weight. This resin was chosen for its relatively fast cure time of 15 minutes at 140°C and its ability to be demolded while still hot because of the high glass

transition temperature during cure. The second material was a carbon-fiber SMC that had higher flow during molding to create complex architectures impossible to do with the prepreg alone (shown orange in Figure 2). The SMC used was Mitsubishi Rayon Pyrofil CVS1016-2BK. This material was chosen for its commercial availability and compatibility with the epoxy prepreg. This SMC contained 53% fiber by weight with a fiber length of 1 in. The final material was a glass-fiber SMC, Continental Structural Plastics 834 SMC (also shown orange in Figure 2). This material was only used on the rear flange of the crush can halves. The switch from carbon fiber to glass fiber in this area addressed a processing issue where the flange was splitting after removal from the mold.

FBCC components were produced by compression molding using two-part tools made of aluminum. A total of three molds were required, including one for 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 in a cycle time of under 15 minutes. 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. 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 measurements. 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. During molding, the parts were placed in the hot mold, cured, and removed from the press. Following molding, the parts were trimmed to final dimensions using CNC milling. Parts were then joined using adhesive bonding and rivets, as shown in Figure 2b.

Material characterization included coupon tests on the prepreg, SMC, and adhesive, as well as component-level hat-section tests (Table 1). The most extensive testing was performed on the prepreg, as that was the primary structural material and expected to contribute most highly to the structural crash response of the FBCC. The SMC and adhesive were characterized to a lesser degree. Hat-section components were manufactured using the same prepreg material and manufacturing process (Figure 3). Hat-section test results were used to tune the material models.

*Table 1: Summary of material characterization testing performed for development of the material models*

<b>CF Prepreg</b>		<b>SMC</b>	<b>Hat-Section</b>	<b>Adhesive</b>
<ul style="list-style-type: none"> <li>• 0° compression</li> <li>• 0° flexure</li> <li>• 0° tension</li> <li>• 0° v-notch</li> <li>• 45° compression</li> <li>• 45° flexure</li> <li>• 45° tension</li> </ul>	<ul style="list-style-type: none"> <li>• 45° v-notch</li> <li>• 90° compression</li> <li>• 90° flexure</li> <li>• 90° tension</li> <li>• 90° v-notch</li> <li>• cyclic tension cross-ply</li> <li>• cyclic tension 45°</li> </ul>	<ul style="list-style-type: none"> <li>• tension</li> <li>• flexure</li> </ul>	<ul style="list-style-type: none"> <li>• 4-point bending</li> <li>• drop tower crush</li> </ul>	<ul style="list-style-type: none"> <li>• lap shear</li> <li>• cleavage peel</li> <li>• impact peel</li> </ul>

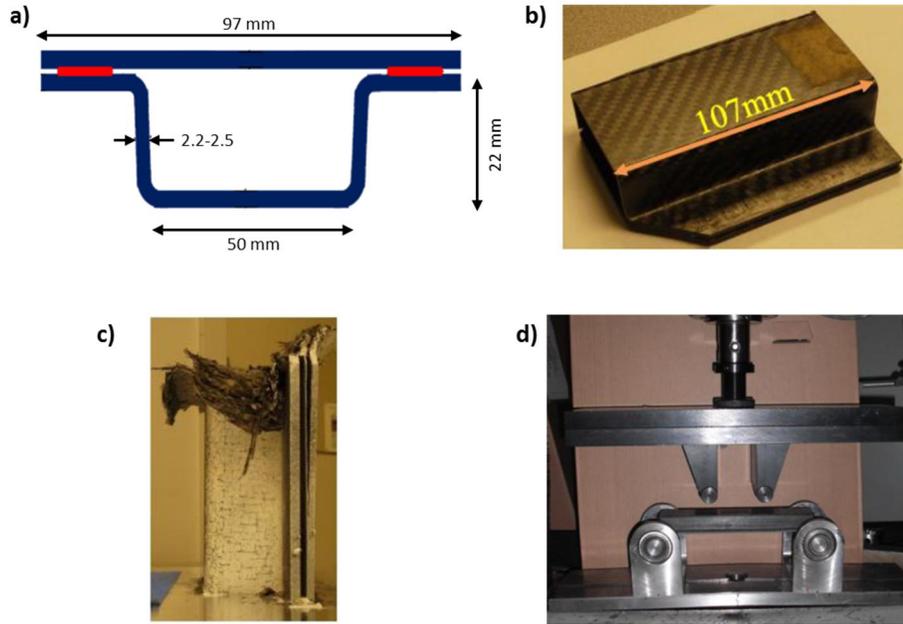


Figure 3: Hat section crush tubes were manufactured from the same material used for the FBCC and tested to help calibrate the material models. a) Dimensions of the hat-section tube. b) An image of a hat-section tube molded, trimmed, and ready for testing. c) A hat-section tube sample following a drop tower test. d) An open hat-section being tested in flexure.

Defects were detected and where possible, analyzed, in FBCC components using both non-destructive and destructive methods. Non-destructive methods included radiograph, ultrasonic inspection, and computed tomography, while cross-sectioning and imaging was the main destructive method. The aim of these inspections was to identify discrepancies between the virtual part design and the actual part that was manufactured. Predictions were based on the virtual part design, and therefore, these discrepancies represent gaps between the modeling and the reality of the build and test. The primary defect in the crush can was distortions of the prepreg due to intrusion of the SMC during molding (Figure 4). The challenge of co-molding the SMC and prepreg, each of which had very different rheological and cure kinetic behaviors, resulted in significant bunching, stretching, and waviness in the prepreg section of the crush can near the flange. These distortions of the fabric are in addition to the distortion caused by draping the prepreg to form the complex shape of the crush can, in comparison to a flat plaque.

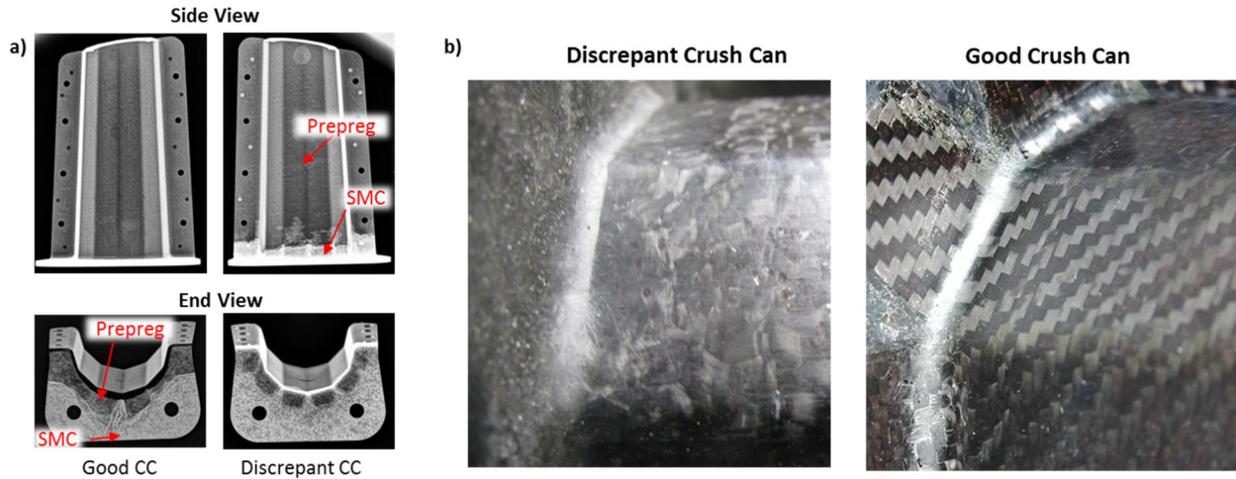


Figure 4: a) Radiographic images of a crush can showing the distribution of prepreg and SMC in a “good” crush can vs. a discrepant crush can. b) Image of the base of a crush can showing the weave pattern in a good vs a discrepant crush can.

It is important to note that the material models used for FBCC crash predictions were primarily based on flat-plaque coupon data, with tuning of the models using the hat-section data. However, this approach does not take into account the effects of manufacturing on material performance. As noted, draping of the prepreg and interaction of the SMC and prepreg in the mold caused distortion of the fabric from its architecture in a flat plaque (Figure 4). To quantify the effect of these distortions, coupons were cut from a crush can and compared to the flat plaque coupon data in longitudinal compression and tension tests. Table 2 shows that the performance of the composite was significantly reduced in the crush can in terms of modulus and strength in both compression and tension.

Defects were also examined on the bumper beam (Figure 5). Both cross-sections and computed tomography showed the presence of extensive porosity in the SMC, as well as resin rich regions and waviness in the prepreg. While the effect of these defects on material properties was not quantified, it is clear that such defects reduced bumper beam performance and may account for some discrepancies between the crash performance and predictions noted later in this paper.

Table 2: Comparison of flat plaques and crush cans tested in compression and tension. Values in red signify the percent reduction in properties.

Test	Modulus (GPa)	Failure Stress (MPa)
Compression Testing		
Flat Plaque	38.5 ± 0.2	446 ± 27
Crush Can Coupons	32.9 ± 2.8 (-14.5%)	352 ± 44 (-21.1%)
Tensile Testing		
Flat Plaque	37.4 ± 0.2	486 ± 20
Crush Can Coupons	37.0 ± 5.8 (-1.1%)	364 ± 86 (-25.1%)

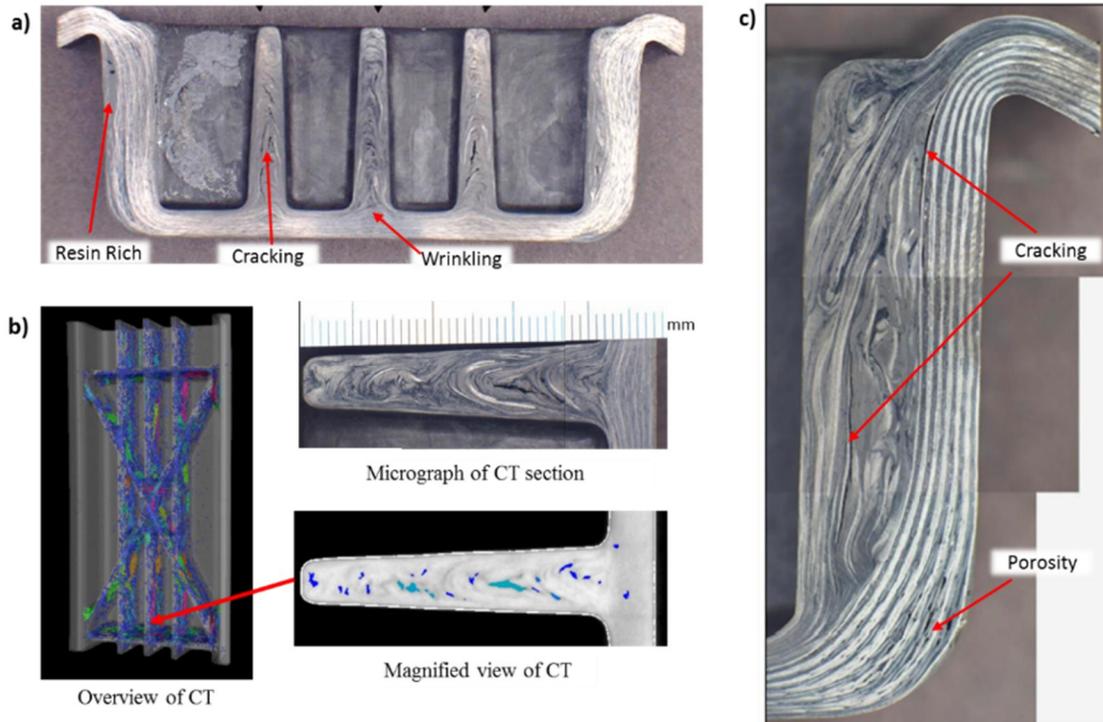


Figure 5: a) Photograph of a cross-section of the bumper beam with several imperfections marked. b) CT images and associated photograph showing porosity in the ribs of the bumper beam. Colors denote the size of porosity with blue corresponding to small pores and red to large pores. c) Micrograph showing cracking and porosity where the SMC ribs meet the interior of the beam fabric.

## Crash Testing Overview

Testing of the FBCC was conducted in six crash modes, including four-high speed and two low-speed modes (Figure 6 and Table 3). Five repeat tests were planned for each mode, requiring at least 30 assembled FBCCs. The high speed modes were aimed at simulating vehicle crashes where the FBCC would need to absorb energy to protect the occupants. The low speed modes simulated low-energy events where, ideally, no permanent damage would occur to the FBCC system, such as a parking lot fender-bender or impact from a loaded shopping cart. Testing of a steel FBCC system was conducted in these same modes to develop test protocols and determine performance benchmarks used to evaluate the carbon fiber system. For all test modes, a sled-on-sled setup was employed (Figure 7). Data acquisition and measurements included 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.

Force vs. time data used for comparison to predictions are shown in Figure 8 for high speed modes and Figure 9 for low speed modes. Data from multiple repetitions in each mode was averaged using a straight-forward time-wise averaging. Because the impact velocity varied little within each crash mode, this method of averaging was deemed suitable. Overall, the test-to-test variation in force, displacement, and acceleration were all found to be minimal. However, only one test at the correct velocity was conducted in the angular test mode and, therefore, predictions were compared to only the results from that test. The angular crash test mode was the most difficult to perform, as the crush can consistently failed prematurely at the base of the sled fixture upon impact leading the team to choose to minimize the number of repetitions.

Although only force vs. time data is presented here for the six crash load cases, displacement and acceleration were also considered when comparing predictions to tests. The zero-time point shown in each plot corresponds to the time of impact and the end time was chosen to best match with the time-window over which predictions were made.

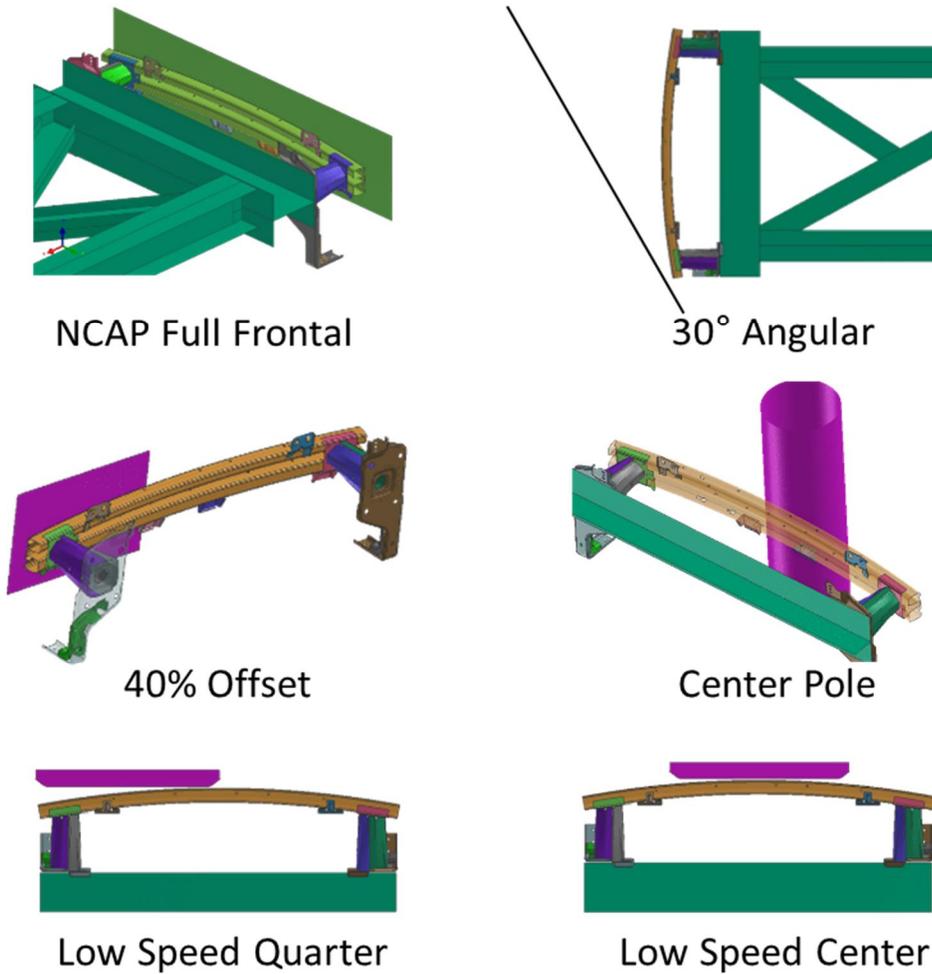


Figure 6: Diagrams of the six crash modes used for FBCC evaluation.

Table 3: Summary of all crash test modes. Values are given as averages and standard deviations.

Crash Mode	Number of Tests Analyzed	Mass (kg)	Impact Velocity (m/s) [S.D.]	Energy (kJ) [S.D.]
NCAP	4	300.00	15.30 [0.24]	33.17 [1.54]
Offset	4	323.00	9.16 [1.98]	13.10 [4.50]
Pole	4	306.00	2.54 [0.16]	1.06 [0.17]
Angular	1	323.00	5.19	4.11
Low-Speed Midpoint	2	302.30	4.56 [0.02]	3.15 [0.04]
Low-Speed Quarter	2	326.40	4.21 [0.26]	2.42 [0.23]

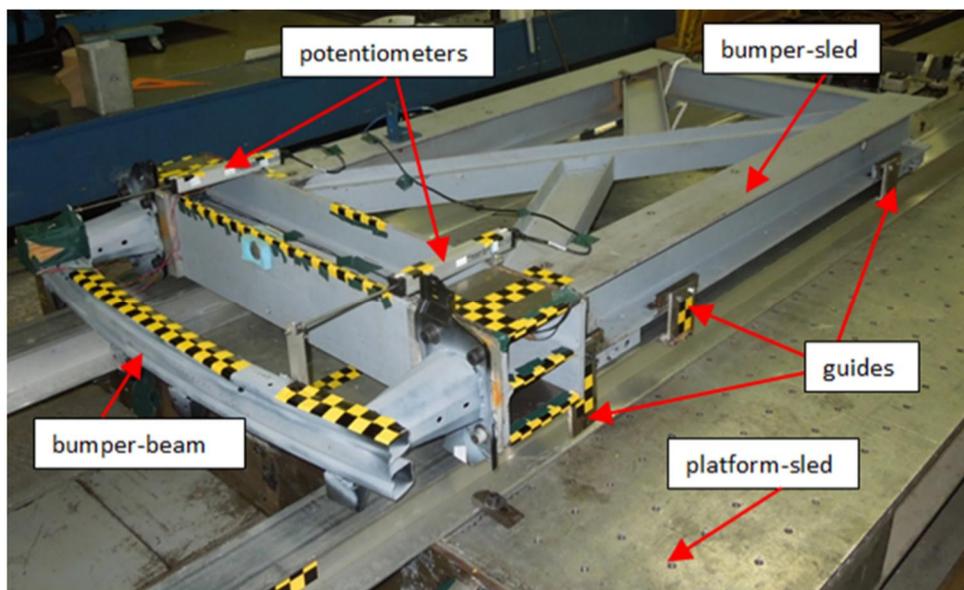


Figure 7: Set-up of sled-on-sled system used for all high-speed test modes

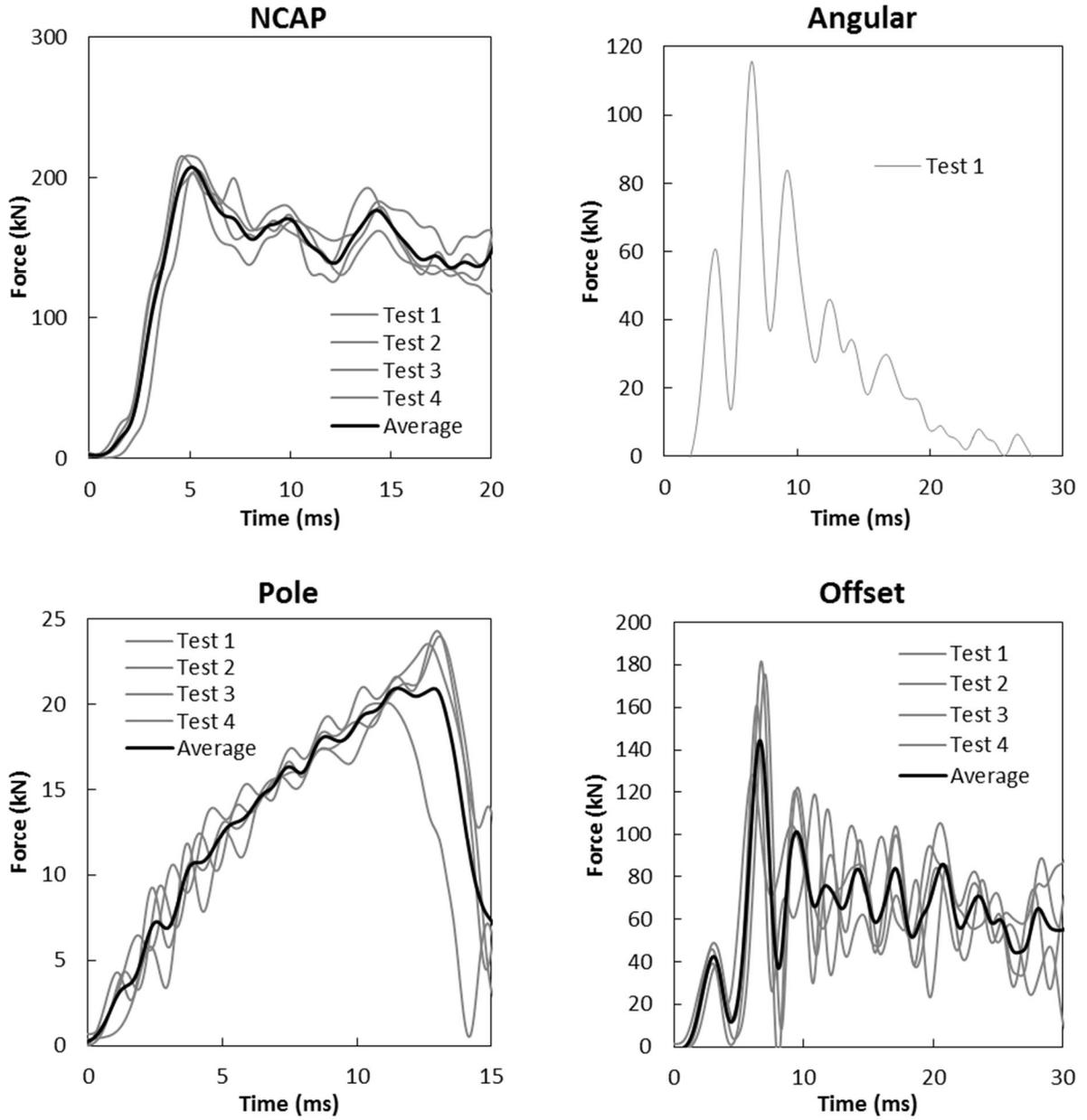


Figure 8: Force vs. time data for the high speed modes, showing the data from each test and the average. Note that for the angular case, only two crash experiments were conducted, of which only one complete dataset was collected.

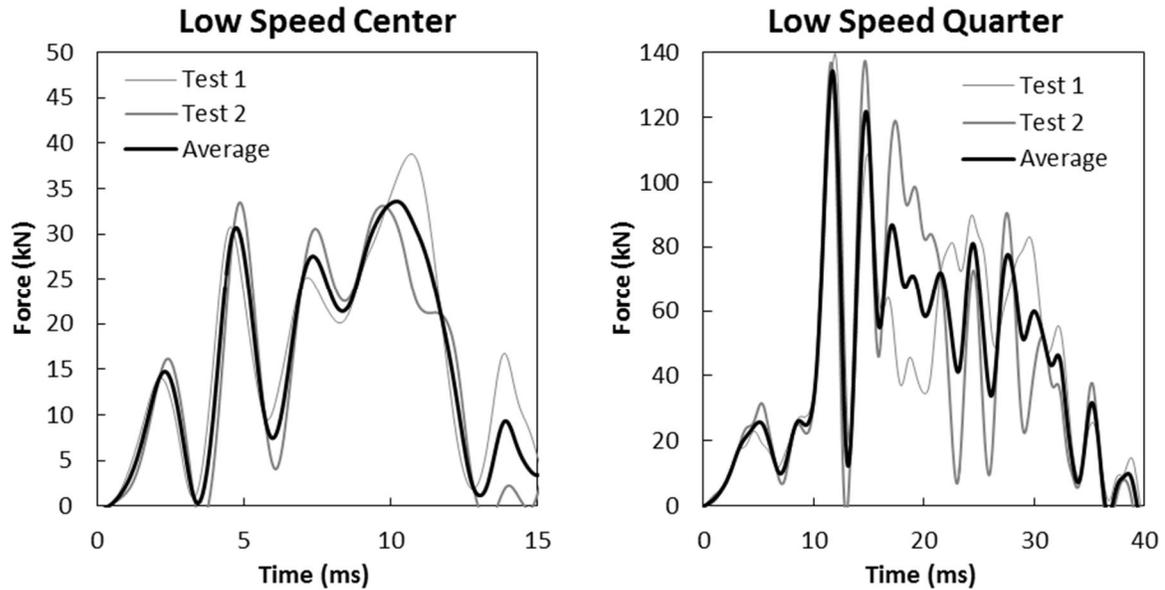


Figure 9: Force vs. time data for the low speed modes, showing the data from each test and the average.

## Comparison of Predictions and Experimental Results

### Quantitative Comparison Methodology

Previously, to compare two non-ambiguous time history signals in passive safety, such as force or displacement, between a numerical simulation and a physical test a rather subjective method was in place. The two signals would be overlaid and given a weighted score based on how good the two fit within a corridor (usually +/- standard deviation). Not until recently, has a more quantifiable approach been proposed. The ISO/TR Standard 16250 (that has been proposed) gives a score from zero to one on how well the two signals correlate. The proposal constitutes two primary drivers: the first, the corridor method where the signals are compared using constant width or sigma based widths and having a weight factor of 40%. The second driver is the cross correlation method that looks at the differences between the two signals with respect to phase shift, amplitude, and slope. Each one of these carries a weight of 20%.

The method described in ISO/TR Standard 16250 was applied to objectively compare the predictions to the physical crash tests. Physical relevance of the scores is described below:

- Excellent: ISO Score > 0.94
  - The characteristics of the reference signal are captured almost perfectly.
- Good:  $0.80 < \text{ISO Score} \leq 0.94$ 
  - The characteristics of the reference signals are captured well, but there are noticeable differences between both signals.
- Fair:  $0.58 < \text{ISO Score} \leq 0.80$ 
  - The characteristics of the reference signal are basically captured, but there are significant differences between both signals.
- Poor: ISO Score  $\leq 0.58$ 
  - There is almost no correlation between both signals.

## Comparison and Correlation Results

Comparison results using ISO 16250 are given in Figure 10 and visual comparisons for each crash mode are given in Figures 11-16. Comparison results indicate that, overall, the accuracy of CAE predictions was mixed with no clear best performers. In terms of average ISO 16250 score, the best predictions came from Software C – Supplier 1, while the worst were from Software B. However, looking closely at the scores for each set of predictions shows that Software C – Supplier 1 had scores as low as 30 and 35, while Software B had scores as high as 55 and 58. On the whole, while some software and suppliers had higher average scores than others, the variation for any given set of predictions was large. Even for the same software, predictions varied greatly from one supplier to the next. Looking closely at both Software C and Software D shows that there were large differences in accuracy of the predictions when comparing one supplier to the other for the same crash mode. For example, for Software C, Supplier 1 scored 86 in NCAP and 35 in LS-Center, while Supplier two scored 49 for NCAP and 70 for LS-Center. Variation in prediction accuracy is also observed from mode-to-mode, with the highest scores on average observed for NCAP and the lowest for Angular. The highest scores were generally achieved for modes that were crush can dominate, including NCAP, IIHS, and LS-Quarter. The lowest scores were generally observed for those where the response was bumper beam dominate, including Angular, Pole, and LS-Center.

Examining the force vs. time and displacement vs. time curves for each mode shows that most predictions did capture the general shape of the crash test responses but simulations generally predicted a stronger composite FBCC than was observed during the test. Force predictions were higher than the forces generated during the crash tests and displacement at any given time was generally lower than the predicted displacement. For example, simulations predicted NCAP forces greater than 200 kN, whereas the actual test response showed forces below 200 kN (Figure 11). The main exception to the ability of the simulations to capture the correct shape of the response was Software B, which did not show similar behavior in terms of shape or magnitude to the actual crash response.

Crash Mode	Software A	Software B	Software C		Software D		Software E	Average
			Supplier 1	Supplier 2	Supplier 1	Supplier 2		
NCAP	62	35	86	49	80	60	37	58
IIHS	67	6	83	55	65	26	46	50
Angular	31	7	30	57	61	29	35	36
Pole	37	58	70	66	42	5	31	44
LS Center	34	55	35	70	40	31	38	43
LS Quarter	65	7	75	73	78	38	64	57
Average	49	28	63	61	61	31	42	

0-20	21-40	41-60	61-80	81-100
------	-------	-------	-------	--------

Figure 10: ISO 16250 results for each prediction. A higher score indicates a better correlation.

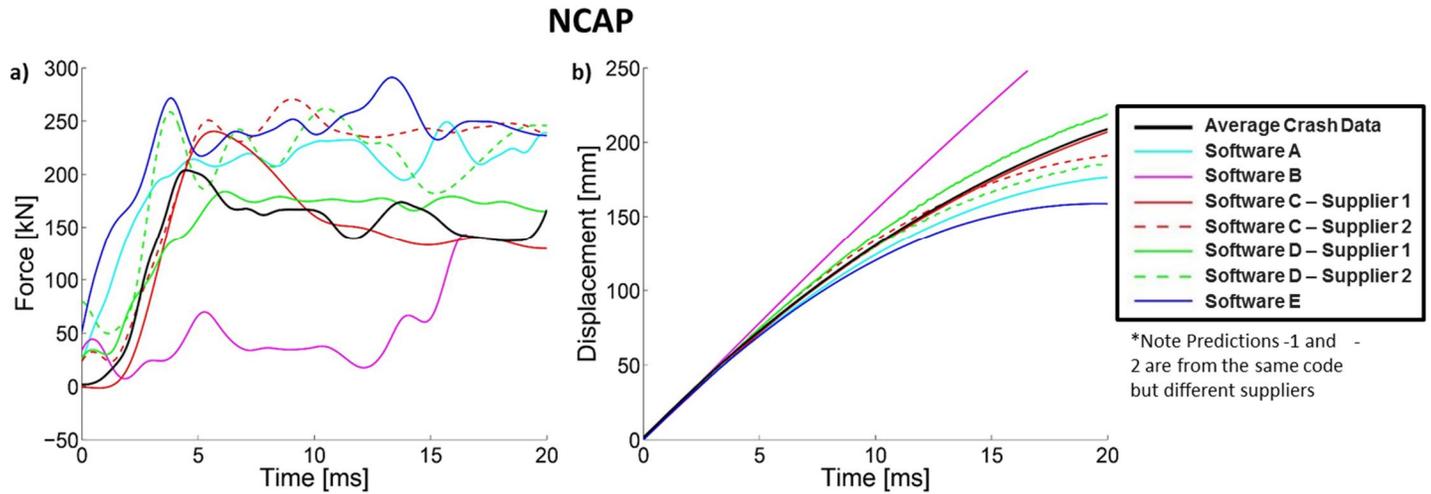


Figure 11: Comparison of each prediction to average crash data in terms of a) force vs time and b) displacement vs. time for the NCAP mode.

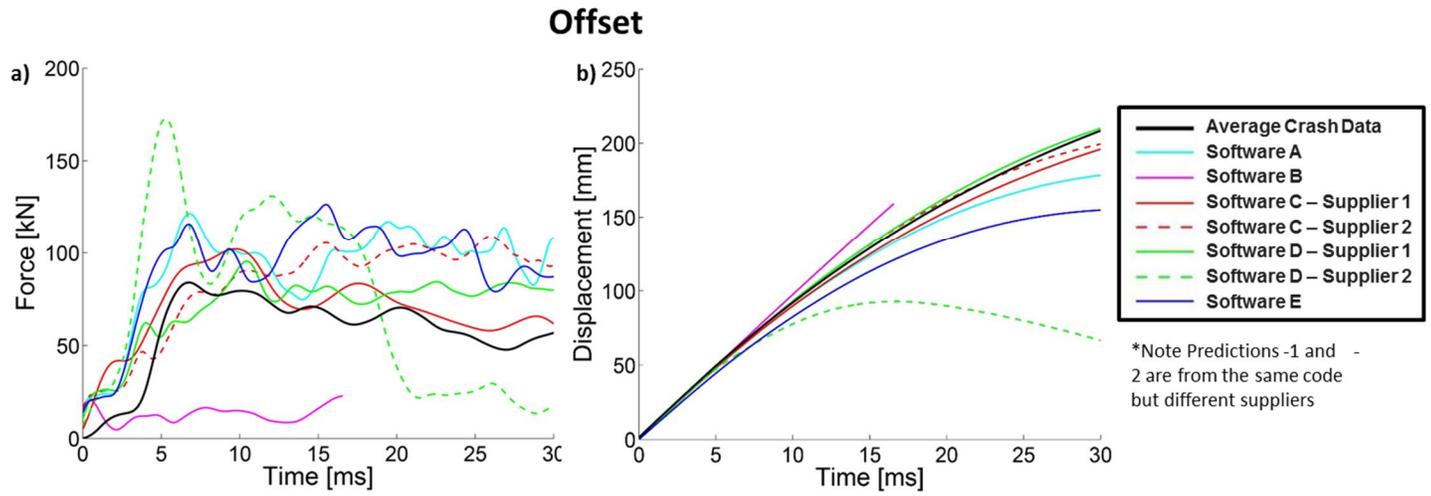


Figure 12: Comparison of each prediction to average crash data in terms of a) force vs time and b) displacement vs. time for the offset mode. Note that the crash data was filtered differently here than in Figure 8, accounting for the different appearance.

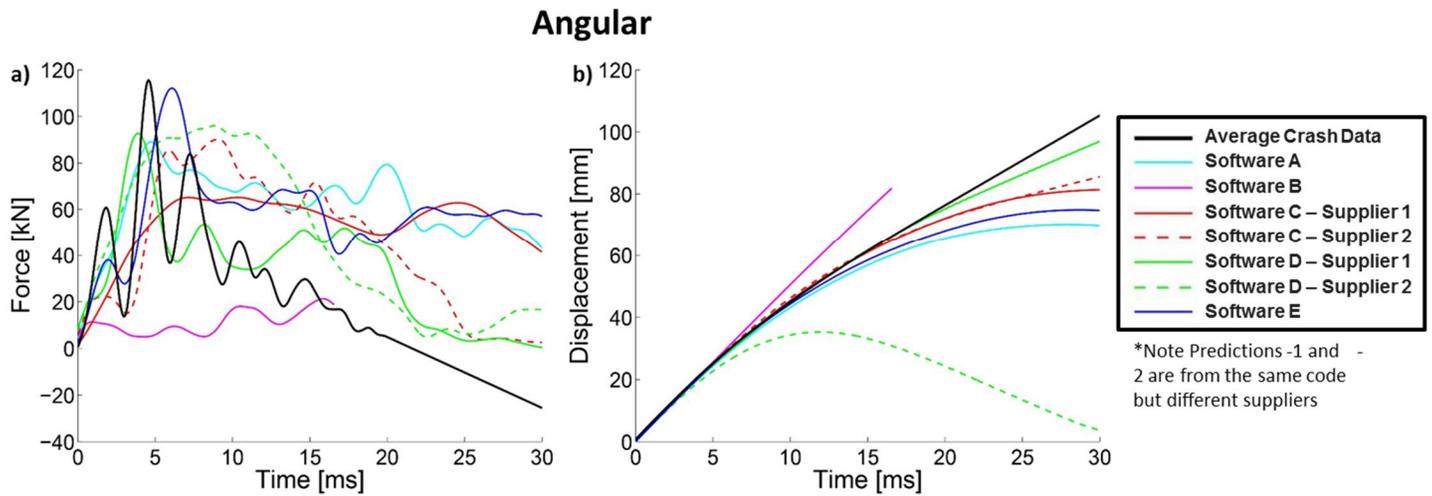


Figure 13: Comparison of each prediction to average crash data in terms of a) force vs time and b) displacement vs. time for the angular mode.

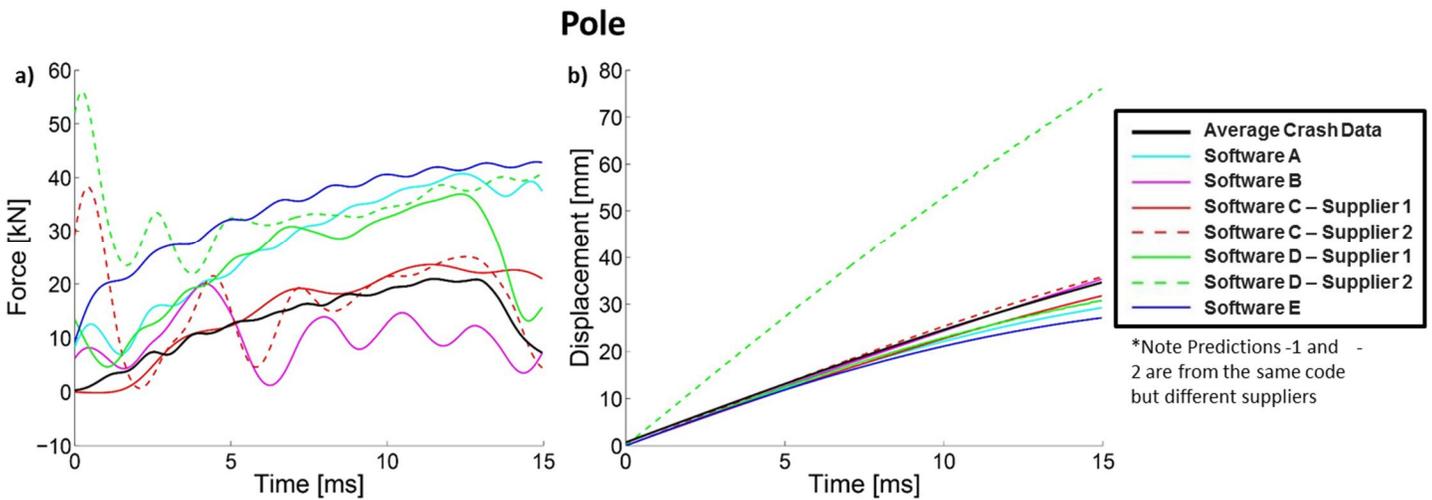


Figure 14: Comparison of each prediction to average crash data in terms of a) force vs time and b) displacement vs. time for the pole mode.

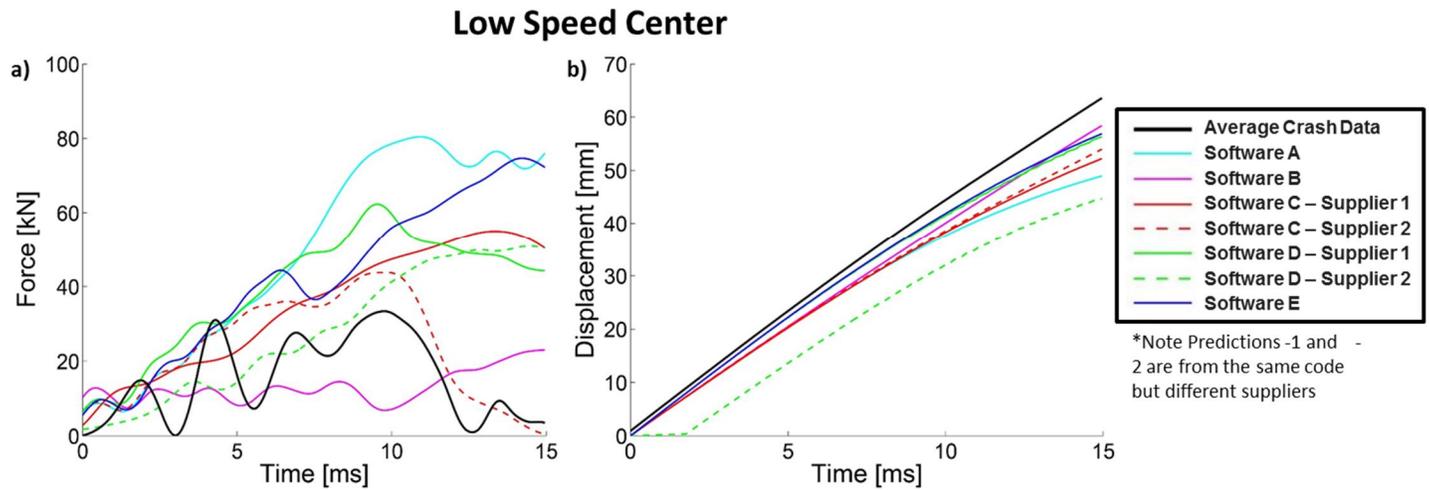


Figure 15: Comparison of each prediction to average crash data in terms of a) force vs time and b) displacement vs. time for the low-speed center mode.

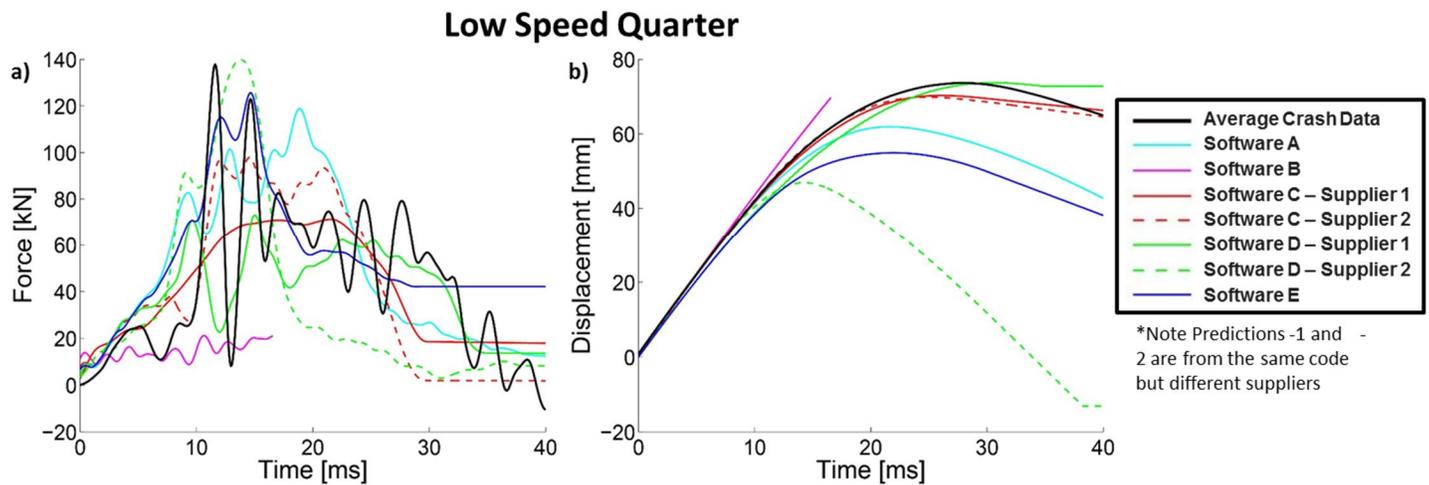


Figure 16: Comparison of each prediction to average crash data in terms of a) force vs time and b) displacement vs. time for the low-speed quarter mode.

## Failure Mode Assessment

The ISO 16250 analysis discussed in the previous section compared the predictions to crash tests based on the FBCC's response in terms of displacement, force, and acceleration. However, this analysis does not examine how well the predictions actually captured the failure modes and overall physics of the FBCCs crash response. Figure 17 shows a comparison between the failure during an angular crash mode test to simulations in Software C from each of the two suppliers. Comparison between the prediction and experiment resulted in an ISO 16250 score of 30 for Supplier 1 and 57 for Supplier 2. While both suppliers showed average force responses of similar magnitude early in the test, Supplier 2 more accurately captured the drop in force near the end of the test. Examining the videos from the crash shows that the FBCC experienced catastrophic failures at the base of the crush can where it meets the flange, as well as at the joint between the

crush can and the bumper beam. These failures happen nearly at the same time and correspond with the drop in force that was measured during the test. Interestingly, when examining the failure locations in each prediction, Supplier 1 captures both the failure at the flange and at the joint, whereas Supplier 2 predicted a split down the crush can that never happened and missed the failure at the flange. In this way, Supplier 1 more accurately captured the physical behavior of the FBCC during the test and it was largely incidental that Supplier 2 more closely matched the force vs. time response.

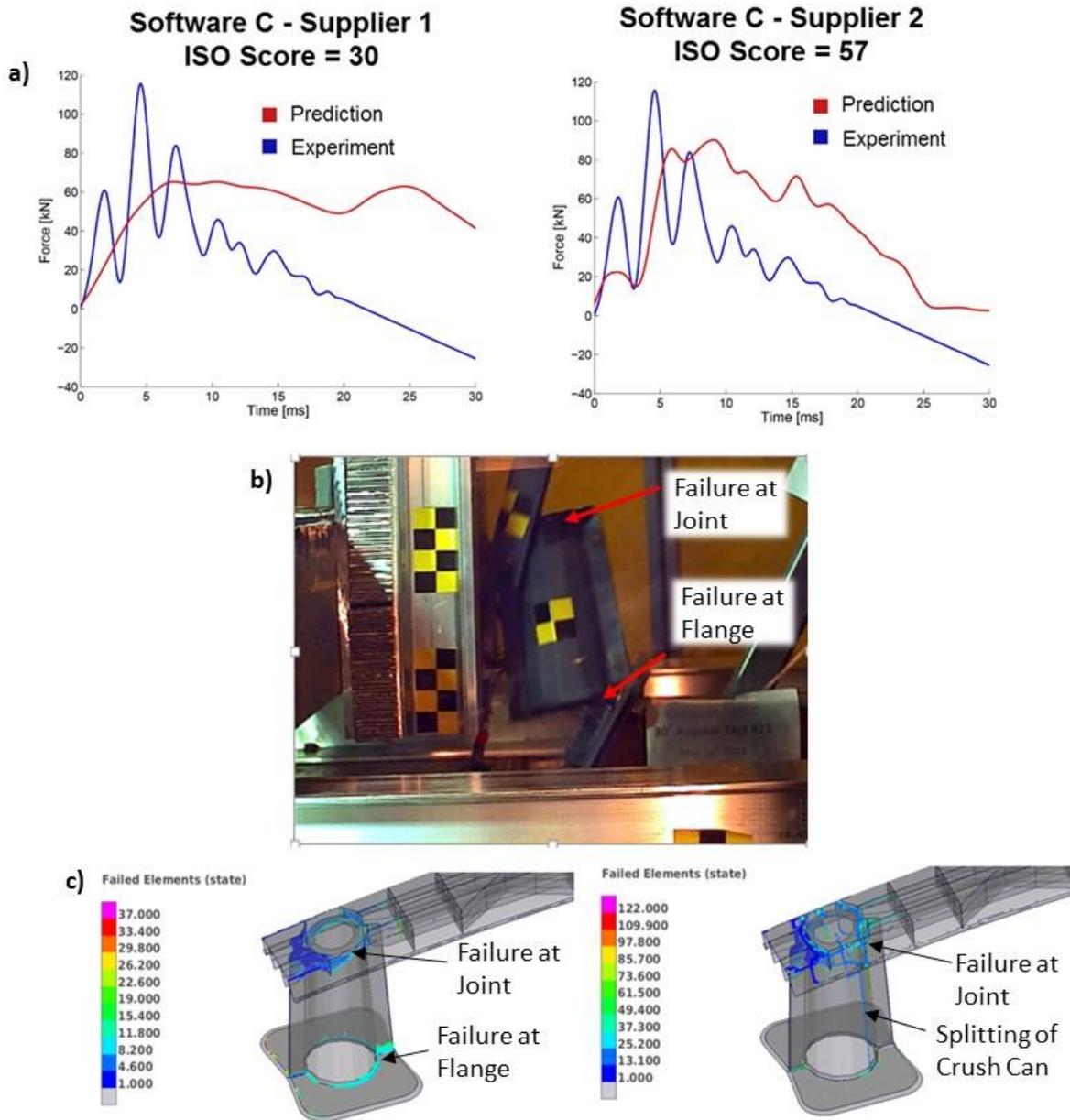


Figure 17: Comparison of crash results from the angular test mode on the composite FBCC to predictions in software C by each supplier. a) Force vs. time curves comparing each predictions from each supplier. b) Image showing the FBCC during the crash highlighting the failure at the base of the crush can. c) CAE predictions showing failed elements at the end of the test. The color scale indicates the time at which the element failed.

The ISO 16250 analysis alone does not fully capture the accuracy of the predictions and an in depth analysis of the predictions is required to understand how closely the experiments and predictions matched. To truly call a prediction accurate requires that the physical behavior is captured such as failure mode and global deformation, in addition to the force, displacement, and acceleration responses. Unfortunately, as noted here, the accuracy of the predictions is further brought into question as a prediction that matched the experiment fairly well in terms of force vs. time did not capture the failure mode, while a prediction that appeared less accurate captured the failure mode quite closely.

### **Steel vs. Composite FBCC Performance**

The target for the composite FBCC was to achieve equivalent structural performance at a 30-35 % mass reduction compared to the steel baseline design. A comparison of the two is shown in Figure 18 and Table 4. The composite FBCC showed a notable reduction in energy absorption, peak load, and average crush load compared to the steel design. However, the composite FBCC was significantly lower in mass, with a 45% reduction compared to the steel FBCC. It should also be noted that no significant optimization effort was expended by the VMM team on improving the performance of the composite FBCC – optimization was not in the scope of the project, but rather, the objective was to ensure that progressive crush was achievable, so that CAE models could be validated. The composite FBCC is able to use the entire crush can length for energy absorption because there is no “crumple zone” (as in metallic structures), accounting for the longer displacement shown for the composite FBCC within the same packaging space. This resulted in the composite crush cans absorbing only 23% less energy despite a 35% reduction in average crush load. Ultimately, it is most advantageous to the vehicle and occupant’s safety to absorb energy at a lower load and with no high peaks, making the flatter load displacement curve of the composite FBCC favorable. Adding mass (i.e. thickness) to the crush cans would result in equivalent energy absorption, while still maintain lower mass than the steel design.

This head-to-head comparison of steel with composite performance was only possible in the NCAP mode with the data collected because the composite FBCC had to be run at lower impact velocities than the steel FBCC in the other modes. In the other modes, the lower performance of the composite FBCC than the steel necessitated reduced impact velocities for more relevant comparisons with predictions.

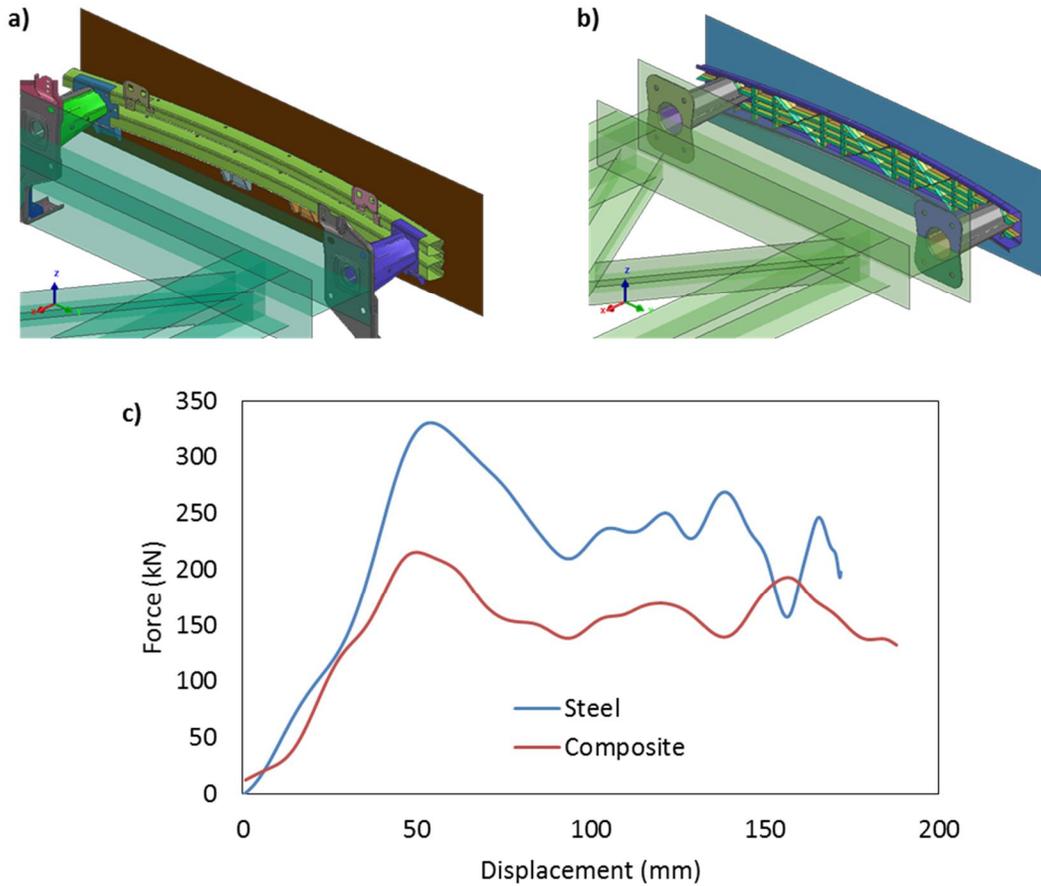


Figure 18: Comparison of the steel FBCC vs. the composite FBCC crash performance in the NCAP mode. a) CAD model of the steel FBCC at the time of impact with the wall. b) CAD model of the composite FBCC at the time of impact with the wall. c) Force vs displacement curves from one representative test for each FBCC type. The data is trimmed at the end at the time in which the crush cans no longer absorbed more energy.

Table 4: Comparison of crash performance in NCAP of the steel FBCC vs. the composite FBCC. The plateau region is defined as the portion of the test between the first peak in load and the end of the curves shown in Figure 18.

	Steel FBCC	Composite FBCC	Percent Change
Mass	10.7 kg	5.8 kg	-45 %
Impact Velocity	15.6 m/s	15.3 m/s	-
Impact Energy	35.9 kJ	33.2 kJ	-
Average Crush Load During Plateau	330 kN	215 kN	-35 %
Peak Crush Load	236 kN	164 kN	-30 %
Energy Dissipated During Plateau	30 kJ	23 kJ	-23 %
Percentage of Impact Energy Absorbed During Plateau	83 %	69%	-

## Identification of Technological Gaps

An important objective of this project was not only to quantify the accuracy of the CAE predictions tools, but also assess the technological gaps that exist between the industry's current approach to predicting crash response of composite automotive structures and the physics of reality. This assessment was supported by a poll of the seven CAE prediction suppliers where the USAMP team asked the following questions:

1. How close do you feel your tool's prediction was to the reality of the test?
2. What do you believe may be the cause(s) of any inaccuracies?
3. What approaches would you suggest to improve these predictions?
4. Do you feel that the material models chosen are sufficient to predict performance of this type of structure?

Through followup interactive discussions, the VMM team and the CAE suppliers reached a consensus on several key areas of technological gaps that exist. These include the ability to characterize the composite materials and fiber orientations, predict the effects of manufacturing, and to characterize the joining of the components. The material models themselves were, by common consensus, found to be less limiting to accuracy than these inputs used to populate the data for the material cards.

A central principle of formulating CAE predictions is that if you put bad data into a model, then you can only expect bad data out. The current approach to material modeling of composites involves characterizing the material in coupons, then inputting this coupon data into the material models. This method is generally used because flat plaques are easy to mold and the tests are well standardized by ASTM, ISO, and other trade/industry groups. A major drawback of such testing is that it doesn't account for variations in material properties resulting from the manufacturing process and the defects that may arise. For example, in the VMM project, significant draping of the prepreg was required when molding the dodecagonal crush cans. This draping realigns the fibers from their original orientation in the flat stack of prepreg layers. In addition, molding pressures on the SMC ribs and backing were found by NDE to cause bunching and stretching of the fabric near the flanges, as noted in Figure 4, which weakened the base of the crush cans. Tests on coupons cut from the crush cans were found as a result to have significantly lower strength and stiffness relative to coupons cut from flat plaques. This was likely the leading cause of the simulations generally predicting the FBCC to have higher structural performance than was observed during crash tests. Therefore, in the VMM project, hat section crush tube tests were conducted to help refine the material models further than was possible with coupon data alone. However, in retrospect, the hat sections did not fully capture all the intricacies of the FBCC manufacturing process, including the actual draping angles, or the interaction of the SMC and prepreg during molding.

Incorporating accurate material data into a CAE model requires a robust framework to tie together predictions of the materials properties and the manufacturing process across length scales. Many modeling tools now exist for predicting manufacturing effects such as draping, resin flow, and cure kinetics. However, bringing all of this data together, with verification by NDE techniques, and using it to predict the effect of manufacturing on material properties is far from trivial. This challenge is addressed by the Integrated Computational Materials Engineering (ICME) approach. ICME ties together design, material selection, manufacturing, and performance predictions. Importantly, both the effect of processing on material structure, and the effect of material structures on material properties is considered.

While composites are often able to achieve part consolidation compared to a metal design, most complex structures still require multiple components, due in part to lack of reliable design guidelines, and non-optimal manufacturing processes. Joining of composite materials in a reliable and effective manner is an area of active research. Methods such as adhesive joining, riveting/bolting, or thermal/ultrasonic welding (in the case of thermoplastics only) are common methods employed. However, the capability for characterization and design of these joints utilizing CAE tools is far from mature and is complicated by the requirement to not only characterize the material doing the joining, such as the adhesive or the rivet, but also the substrate and the interface between each component. This often means that testing conducted for an adhesive on one substrate is not relevant to its performance with a different substrate, even if the substrates are the same material with different thicknesses. In the VMM project, this challenge of characterizing and designing the joints became apparent through the results of FBCC crash testing for the angular and pole modes. Unfortunately, this happened too late in the project sequence to permit further iteration in the joining process. In these modes, the premature failure of the joint between the crush cans and the front bumper led to greatly reduced FBCC performance compared to design intent. All of the predictions assumed a perfect bond at these joints due to the challenge and complexity of modeling the joint more accurately, which led to the models greatly over-predicting FBCC crash performance in these modes. While much of the gap here is in development of the modeling methods, a separate research effort focused on accurate and efficient experimental characterization of these joints would greatly aid in improving these predictions in future.

## **Conclusions**

Modeling methods for simulating behavior of carbon fiber composites during crash are continuously improving, but still have a long way to go before they can be considered truly predictive and reliable. Accurate modeling requires a combination of robust best practices, and a strong level of user expertise and experience with the software packages and material models. Overall, it was observed that the CAE suppliers that had a proven track record with the software package they were using generated more accuracy predictions than those that did not. This arises from the fact that developing the material cards for finite-element analysis and selection of computational routines still requires a large amount of subjective tuning to best match failure modes and element deletion criteria with the available material test data, as well as a sound perspective on how that material will perform during the actual test. No set of predictions from a supplier were found to be universally accurate among all of the six crash modes, with the best performer having an average ISO 16250 score of 63, but also a wide ISO score range with a low of 30 and high of 86. Most software packages had the tools available to provide reasonable predictions, with the exception of Software B. Yet still, there was much variation in the average ISO 16250 scores from code to code and because the results varied with supplier, it is impossible to fully assess what differences can be attributed to the software versus what could be attributed to the expertise of the CAE practitioner, without undertaking further expansive studies on this aspect. Crash modes that were most dependent on the properties of the prepreg were more accurate than those that were heavily dependent on the behavior of the joints and SMC.

Much of the unreliability of the predictions can be attributed to shortcomings in our ability to mathematically link the effects of manufacturing and material variability into the material models. Coupon tests alone are not sufficient to develop an accurate material model and it is necessary to bridge the gap between the coupon data and the actual structure with a series of subcomponent level tests. The selection of these subcomponent tests and the application of their results to tuning the material models is, again, heavily dependent on the expertise of the modeler. ICME techniques show promise for creating a framework to take manufacturing and material microstructure simulations and apply them to structural predictions, but the tools are still under

development and not yet industry standard.

## **Acknowledgements**

This program is supported by the U.S. Department of Energy under Cooperative Agreement Number DE-EE0005661 awarded to the United States Automotive Materials Partnership. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This is a collaboration involving over 90 researchers and at least 30 organizations. The authors would like to thank each organization and the individuals that participated in this project for their invaluable contributions.

## **References**

1. Coppola, A.M., L. Berger, D. Board, M. Jones, J. Truskin, and M. Mehta. "Validation of Material Models for Crash Testing of Carbon Fiber Composites: Overview," SPE ACCE, Sept 2016, Novi, MI.
2. Board, D., Y. Chen, O. Faruque, G. Li, G. Newaz, P. Begeman, A. Yaghoubi, and Y. Dixit, "Validation of Material Models: Physical Crash Testing of Composite Bumper-Beams," SPE ACCE, Sept 2016, Novi, MI.
3. Coppola, A.M., L. Berger, G. Smith, D. Armstrong, and C.J. Dasch, "Validation of Material Models: Thermoset Composite Materials and Processing For a Composite Bumper-Beam System," SPE ACCE, Sept. 2016, Novi MI.
4. Trameçon, A., M. Doroudian, R. Dwarampudi, P. Pasupuleti, L. Berger, O. Faruque, Y. Chen, and J. Truskin, "Validation of Material Models: Design of a Composite Bumper-Beam and Assessment of Current Composite Crash Simulation Capabilities," SPE ACCE, Sept 2016, Novi, MI.
5. Stevens, H. & A. Cawley, "Validation of Material Models: Joining and Assembly System for Thermoset & Thermoplastic Composite Materials," SPE ACCE, Sept 2016, Novi, MI.
6. Jin, X., M. Doroudian, H. Yu, P. Pasupuleti, D. Armstrong, L. Berger, O. Faruque, and J. Truskin, "Validation of Material Models: Composite Fabric Manufacturing Studies by Simulation and Experiment," SPE ACCE, Sept 2016, Novi, MI.
7. McHenry, J. & J. Tao, "Validation of Material Models: Development of Carbon Fiber Reinforced Thermoplastic Composites for a Front-Bumper/Crush-Can System," SPE ACCE, Sept 2016, Novi, MI.
8. Dasch, C.J., G.J. Harmon, and M.H. Jones, "Validation of Material Models: Non-destructive Testing Throughout the Development of a Carbon-Fiber Composite Automotive Front-Bumper/Crash-Can Structure," SPE ACCE, Sept 2016, Novi, MI.