Validation of Material Models for Crash Simulation of Automotive Carbon Fiber Composite Structures (VMM)

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US Automotive Materials Partnership

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LM084

Project Overview

TIMELINE

❑ **Project start date: 6/1/2012**

❑ **Project end date: 11/30/2016**

❑ **Percent complete: 50%**

BUDGET

- Total project funding

  DOE share: $3,445,119

  Contractor share :$3,445,119

- Funding received in FY14
  $788,701

- Funding for FY15:

  DOE share: $1,031,166

  Contractor share:$1,031,166

BARRIERS

- **Predictive Modeling Tools**
  - Validation of carbon fiber composites material models for crash simulation, which will be demonstrated via design, analysis, fabrication, and crash testing.
- **Manufacturability**
  - A material and process system to manufacture in high volume an automotive crash structure with carbon fiber composites
- **Joining & Assembly**
  - High-volume, high-yield joining technologies for lightweight and composite parts need development and validation for crashworthiness.

PARTNERS

- Northwestern University (sub-awardee)
- University of Michigan (sub-awardee)
- Wayne State University (sub-awardee)
- National Center for Manufacturing Sciences
- ESI North America, Inc.
- Continental Structural Plastics
- Highwood Technologies
- **Project Lead: USAMP (GM, Ford, Chrysler)**

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Objective - Relevance

Objective: Validation of Carbon Fiber Composite (CFC) Material Models for Crash Simulation of Automotive Structures

Project Goal:

❑ Validate existing CFC material models in commercial crash codes and a selected number of models developed by previous Automotive Composites Consortium (ACC) with academic partners leveraging DOE funds. This will be accomplished by fabricating a representative CFC Front Bumper and Crush Can (FBCC) System, conducting crash tests and performing predictive crash simulations for critical high and low speed impact cases.

Relevance to DOE Vehicle Technologies Mission:

❑ Successful validation of material models will enable designing light weight crashworthy automotive structures with production-feasible carbon fiber composites for significant mass savings, improved fuel economy and environmentally friendly future vehicle development.

Approach

❑ *Experimental and Analytical Characterization of Crash Testing of a Steel FBCC*

> To obtain the design targets for the composite FBCC design, a steel FBCC from a current production vehicle will be tested in both high-speed and low-speed crash modes. Analyze data to establish the targets for the composite design.

❑ *Design of the composite FBCC*

- ▪ *Select carbon-fiber material and process system*

  > At least one material and process system (MPS) suitable for high-volume manufacture (~ 100,000 parts per year) of a carbon-fiber composite will be selected for this project.

  > Plaques and simple shapes will be made with this MPS, and the appropriate material properties determined.

- ▪ *Select joining strategy*

- ▪ *Iteratively design a composite FBCC*

  > The composite FBCC will be designed, in conjunction with the Materials and Process team, via an iterative process using commercial crash codes and previously-developed ACC materials models for analysis, with the targets from the steel FBCC crash.

Approach, continued

❑ **Manufacture and assembly of the composite FBCC**

- ▪ *Develop the fabrication process for the composite FBCC*

  Tooling will be designed and fabricated for the selected design and MPS. While initial fabrication trials may use glass fiber composite, final trials and prototypes will use carbon fiber composite.

- ▪ *Fabricate and assemble the FBCC*

  Crush cans and bumpers will be fabricated and assembled into the FBCC.

❑ **Crash testing of the composite FBCC**

- ▪ Test the composite FBCC at the determined static and dynamic load cases. Sufficient repetitions will be performed to establish reproducibility comparable to steel.

- ▪ Failure modes will be analyzed to determine part-to-part variability.

- ▪ Test data will be analyzed to obtain critical crash responses for the composite FBCC which characterize the dynamic forces, deceleration, and transient energy absorption measured during the crash test.

Approach, continued

❑ **Non-Destructive Evaluation of Composite Structure**

▪ *Pre- and post test NDE of selected composite FBCC*

NDE methods will be evaluated and developed for the selected MPS. The composite FBCC system will be nondestructively inspected both before and after testing. This will include joints and joint strength, and the properties of the composite materials.

▪ *Evaluating NDE methods to monitor "health" of composite structure*

Methods will be evaluated for in-service monitoring of the composite structure. Methods may include the use of fluorescent dye in microcapsules, bulk resistivity measurements, resistance of a conductive fiber woven into the structure and capacitive measurements, as well as other methods TBD.

Approach, continued

❑ ***Comparison of the Experimental Results with the Analytical Predictions***

▪ *Comparison of the Steel and Carbon-fiber Composite FBCC*

The results of the physical testing of the carbon-fiber composite FBCC will be compared with the critical response targets determined from the steel FBCC to determine equivalency of performance.

▪ *Correlation of Physical and Analytical Results*

The crash response predictions from the commercial models and previously-developed ACC models will be compared to the physical test results to establish the predictive capabilities of these material models.

All analytical model predictions will be compared with each other, to determine the relative utility of these models.

Milestones for FY2014 and 2015

M1	*Crash Test Fixtures for Steel FBCC Complete*	12/20/2013	Complete
M2	*Steel FBCC Predictions Complete*	7/31/2014	Complete
M3	*Steel FBCC Crash Testing and Targets for Composite FBCC Design Complete*	2/28/2014	Complete
M4	*Composite Material Property Testing Complete*	10/31/2014	Complete
M5	*Composite Material and Process System Selection Complete*	6/30/2014	Complete
M6	*FBCC Design 1 Released for Tooling Kickoff*	9/30/2014	Initial Consultation Held with Tool vendors
M7	*Composite FBCC CAD Design 1 Complete (including initial CAE and manufacturability analysis)*	12/5/2014 5/31/2015	Unidirectional CF crush-can complete; Woven CF crush-can
M8	*Composite FBCC Design 1 Crash Predictions Complete*	8/1/2015	Anticipated

Technical Accomplishments:
Crash Testing of Baseline Steel FBCC & Design Targets Setting

❑ **All Crash Testing and data analysis were completed.**

❑ **Targets were set for the Composite FBCC Design:**

  ▪ Load, Crush distance, Pulse, etc.

  ▪ Energy Absorption

❑ **Simulation of all impact events has been completed for the for Steel FBCC crash tests in 4 commercial codes**

  ▪ High Speed and Low Speed
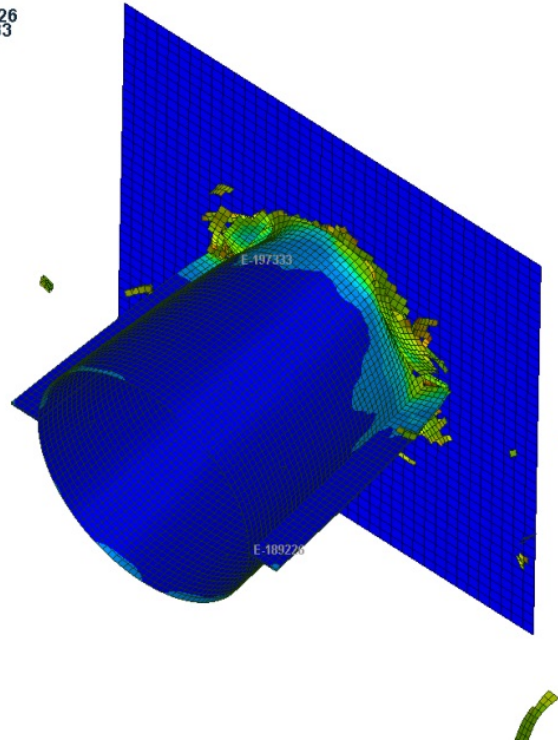
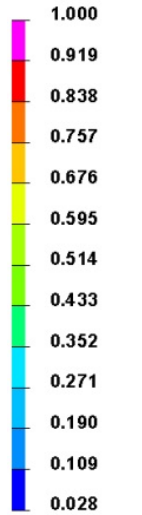# *Technical Accomplishments:*
Design of Composite FBCC

❑ **A comprehensive material property matrix was developed to meet the needs of academic material model partners and commercial codes.**

- University of Michigan Meso-scale Representative Unit Cell (RUC) Model (Waas) and Northwestern University Microplane Model (Bazant)

- PAM-CRASH, RADIOSS, LS-DYNA, ABAQUS

- Material properties necessary for academic and commercial material models were measured.

- Includes - standard tensile, compression, and shear, as well as cyclic tension and compression, size effect testing and rate effect tests.
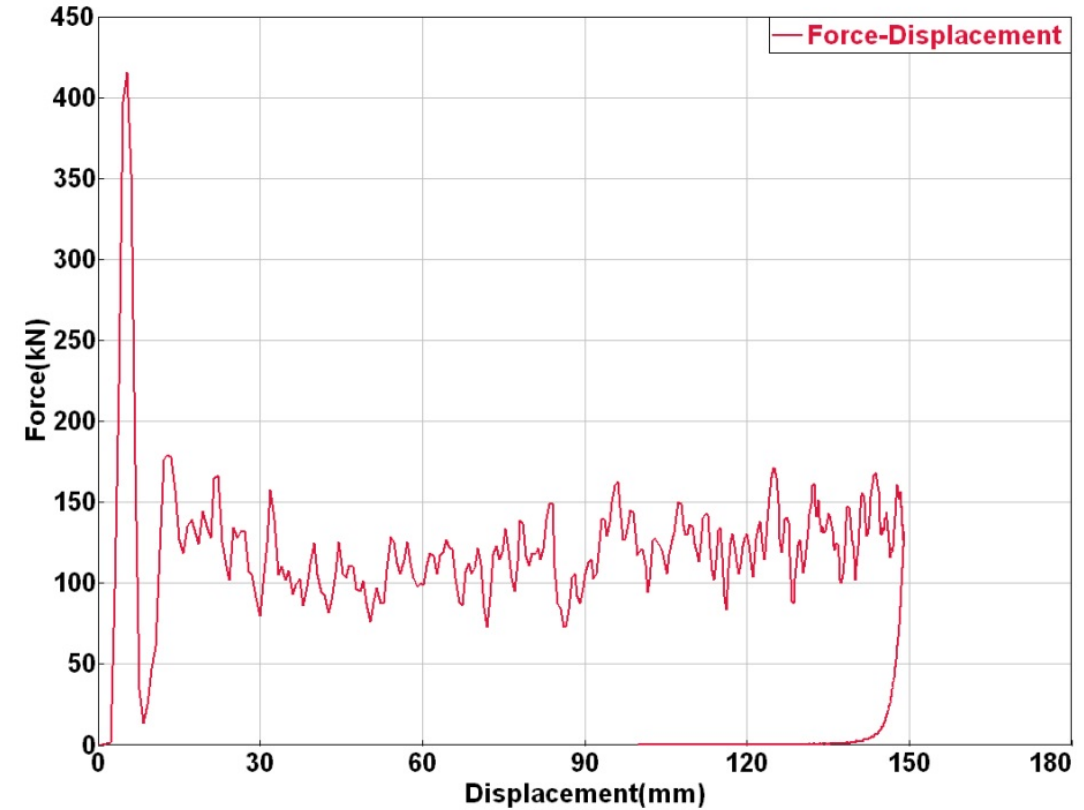
❑ **Selection of Material and Process System**

- Carbon fiber twill weave/epoxy pre-preg and random carbon fiber SMC were selected as the material, to be fabricated by compression molding.

Technical Accomplishments:
# Design of Composite FBCC, continued

Preliminary analysis results for 2-piece conical crush can concept

Technical Accomplishments:
Design of Composite FBCC, continued

❑ **Engineering activity focused on completing analysis of section profiles and simulating crush characteristics (peel or axial crush modes) for the crush can and bumper beam, by applying new material property data measurements to calibrate UM and NWU models.**

❑ **Analysis of simple hat-section components and crush tubes was done.**

❑ **Design was down-selected to C-channel (twill weave and unidirectional with SMC ribs of chopped random) with two-piece flanged conical crush cans, to be fabricated with compression molding.**
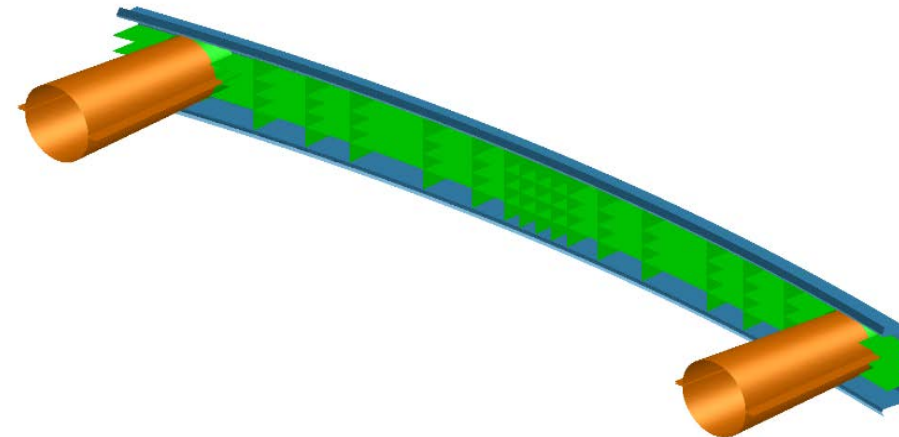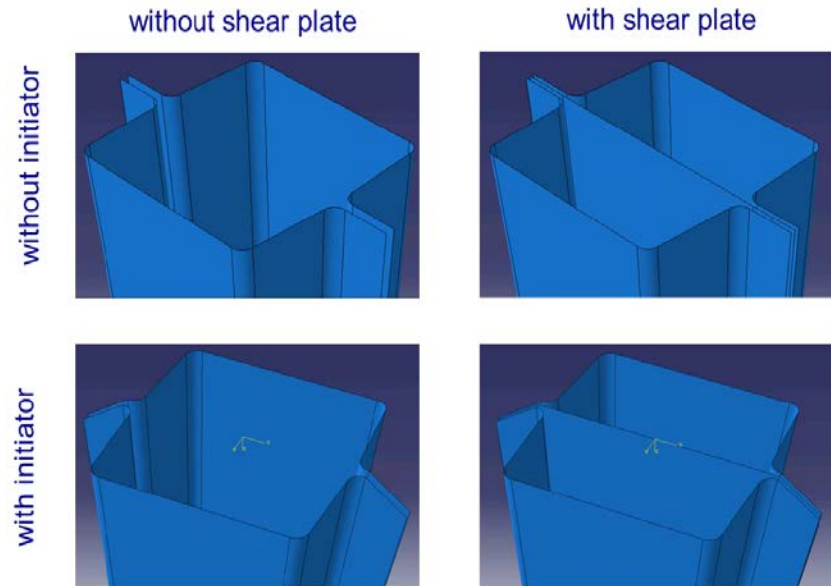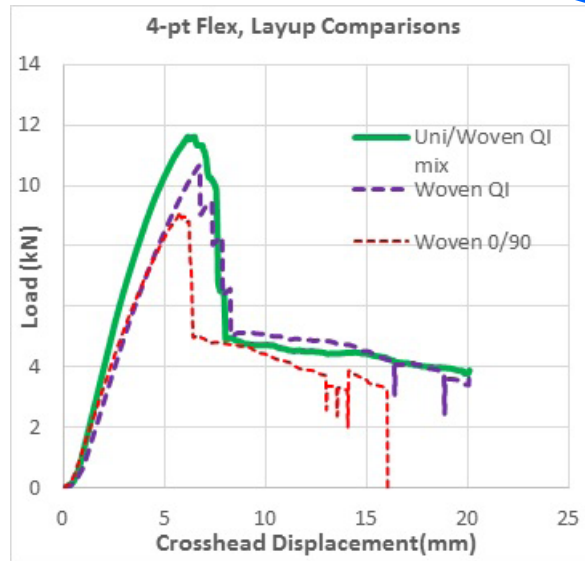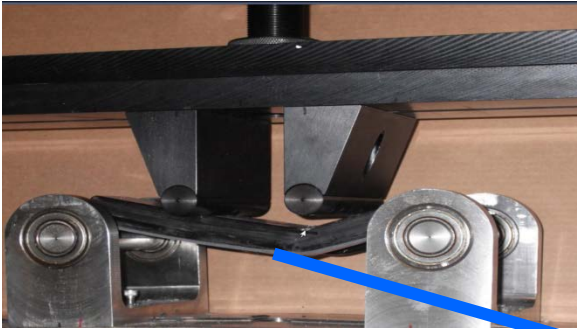

Designs for the crush cans made from two compression-molded conical hat sections joined at the flanges, and the bumper beam, a C-channel with ribs, also compression molded.
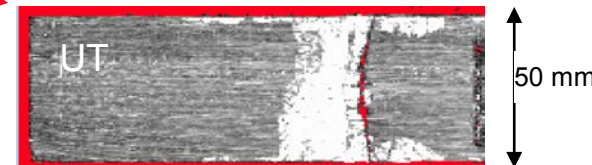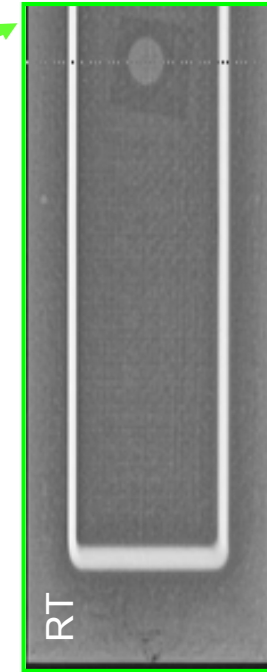
Technical Accomplishment:
Non-Destructive Evaluation of Impact and Flex Damage

4-pt Flex:
Closed hat section taken to failure

4-pt Flex, Layup Comparisons

Load (kN) vs Crosshead Displacement(mm)

— Uni/Woven QI mix
-- Woven QI
-- Woven 0/90

Curves are an average of 4 parts per layup. The saw-tooth effect at the end of the displacement is an artifact of the averaging.

Several types of potential in-service damage were induced on carbon fiber composites Including:

- **Flex failure on a closed hat section**
- **Out-of-plane impact on a plaque**
- **Compression after impact testing of plaques.**
- **These samples were then imaged by ultrasound and X-ray methods, and the results compared.**

RT

UT

50 mm

Woven 11-ply [(0/90/45/-45/90),0]$_s$, 2.4-mm thick

Responses to Reviewers Comments (FY 2014 AMR)

We appreciated the overall positive feedback last year. A few comments can be addressed.

Question 1: A reviewer asked about targets.

These were set this year from the crash data for the steel sub-system. The target energy absorption was set as 17 to 19 kJ and average force of approximately 110 kN. The question of the rails being able to withstand these forces is not relevant as we are not designing to a specific vehicle.

Question 6: A reviewer asked about milestone slippage.

Some milestones are behind because of contracting issues with vendors, and the need for more specialized testing and material property data measurements for the academic models. These issues created a domino effect on the information needed for design. We still anticipate that we will be able to finish the project on time.

Collaboration with other institutions

- ❑ **Northwestern University**

  - ▪ Sub-recipient. Collaboration is within the VT program

  - ▪ Northwestern is one of the key members of our team. Prof. Bazant has worked with ACC for a number of years on the Micro-plane RUC model. He and his team are predictively modeling the crush cans for this project, to determine if their model can be validated in an automotive crash scenario.

- ❑ **University of Michigan**

  - ▪ Sub-recipient. Collaboration is within the VT program

  - ▪ U of M is one of the key members of our team. Prof. Waas has worked with ACC for a number of years on the Meso-Scale RUC model. He and his team are predictively modeling the crush cans and bumper beam for this project, to determine if their model can be validated in an automotive crash scenario.

- ❑ **Wayne State University**

  - ▪ Sub-recipient. Collaboration is within the VT program

  - ▪ Wayne State is providing the crash testing for the project, including high speed sled tests and lower speed pendulum tests. Prof. Newaz and his team are participating with equipment development, testing, and analysis.

Collaboration with other institutions, continued

❑ **National Center for Manufacturing Studies**

- Vendor. Collaboration is within the VT program.
- NCMS is the technical project manager for the VMM project.

❑ **ESI**

- Vendor. Collaboration is within the VT program.
- ESI is the prime engineering vendor, responsible for the predictive analysis of the steel FBCC and the design and predictive analysis of the composite FBCC, using commercial codes.

❑ **Continental Structural Plastics**

- Vendor. Collaboration is within the VT program.
- CSP is the major composite fabrication supplier, responsible for fabrication of plaques and simple shapes for materials evaluation, and fabrication/assembly of the composite FBCC.

❑ **Highwood Technologies**

- Vendor. Collaboration is within the VT program.
- Highwood Technologies is responsible for the development of NDE for the carbon fiber composites, as well as the investigation of structural health monitoring methodologies.

Proposed Future Work

- ❑ **FY 2015**

  - Complete the design of carbon fiber composite FBCC, based on targets obtained from baseline steel.

  - Procure tooling for the compression molding of the composite FBCC.

  - Conduct the initial molding trials of the crush cans and bumper beam, and develop a stable process for molding. Establish the assembly and joining process.

  - Predictively model the crash test results for the composite FBCC.

- ❑ **FY 2016**

  - Crash test the composite FBCCs.

  - Analyze data and compare to the predictions.

  - Investigate secondary design of FBCC for unconstrained packaging, with alternative carbon fiber composite materials.

  - Develop methodologies for NDE and Structural Health Monitoring (SHM) of a system with the materials, geometry, and joining of the composite FBCC

- ❑ **FY 2017**

  - Complete final report

VMM Project Summary

- ❑ **Relevance**
  - ▪ The *validation of crash models for carbon-fiber composites* enables the use of production-feasible composites in *automotive primary structures* including crash and energy management applications, thus *saving mass* and *increasing transportation energy efficiency*.
- ❑ **Approach**
  - ▪ *Design and build* a composite FBCC that meets the targets of a production steel system, *predict* its performance based on commercial and academic material models, *crash* the composite structure, and *correlate* the design predictions with the crash results.

- ❑ **Technical Accomplishments**
  - ▪ *Crash* testing of *steel FBCC* and establishment of design targets for *composite FBCC*
  - ▪ *Design* and CAE completed on several options for *crush cans and bumper beam*
  - ▪ Selected *material and process system* based on *thermoset composite test data*
  - ▪ Evaluated adhesive materials and joining strategies for carbon-fiber composites
  - ▪ Compared and evaluated *NDE methods* for carbon-fiber composites

- ❑ **Collaborations**
  - ▪ Northwestern University, U of Michigan, Wayne State University
  - ▪ Vendors for predictive design, composite structure fabrication, NDE, and project management .

- ❑ **Future work**
  - ▪ Complete the predictive analysis of final FBCC design using candidate material models (FY2015)
  - ▪ Complete the molding and assembly of composite FBCC (FY2015)
  - ▪ Crash-test the composite FBCC (FY2016)
  - ▪ Correlate crash results with the predictive analysis (FY2016)