VALIDATION OF MATERIAL MODELS: THERMOSET COMPOSITE MATERIALS AND PROCESSING FOR A COMPOSITE BUMPER BEAM SYSTEM

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Abstract

The objective of this four-year, $7 million U.S. DOE and 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.[1] 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 simulation 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 summarizes the materials and processing procedures used to manufacture the front bumper and crush can (FBCC) system, with a focus on thermoset-matrix composites. The materials and processing selection and validation is based on a design-build-test strategy that relies heavily on prediction at all stages of the process. The FBCC system uses compression molded carbon fiber/epoxy prepreg for primary structural zones and carbon fiber/vinyl ester sheet molding compound for geometrically complex architectures. Results from material screening tests will be reported. Manufacturing details including layup, preforming, and molding procedures are described. Several issues that arose and potential or implemented solutions are also discussed.

Thermoset Composite Materials and Processing Objectives

- The first goal of this subset of the VMM project is material and processing selection. While this is a research effort and not directly aimed at the production of a commercial automotive subsystem, it is important to ensure that we are studying materials and processes that could be used in automotive production. In particular, a path towards rapid processing has been a key factor.
- The second goal of this subset is to manufacture the composite FBCCs for crash testing. A total of 50 FBCCs were produced, with three used for the development of non-

destructive evaluation (NDE) techniques and the rest for crash testing. The NDE of the FBCCs helped identify manufacturing defects that translated to gaps between the modeling prediction and the crash test results.

FBCC Design Summary

The FBCC is composed of five parts, including the beam and the two crush cans, which are each composed of one “A” and one “B” part (Figure 1). The crush cans are designed as two halves of a tapered cylinder that 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 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.

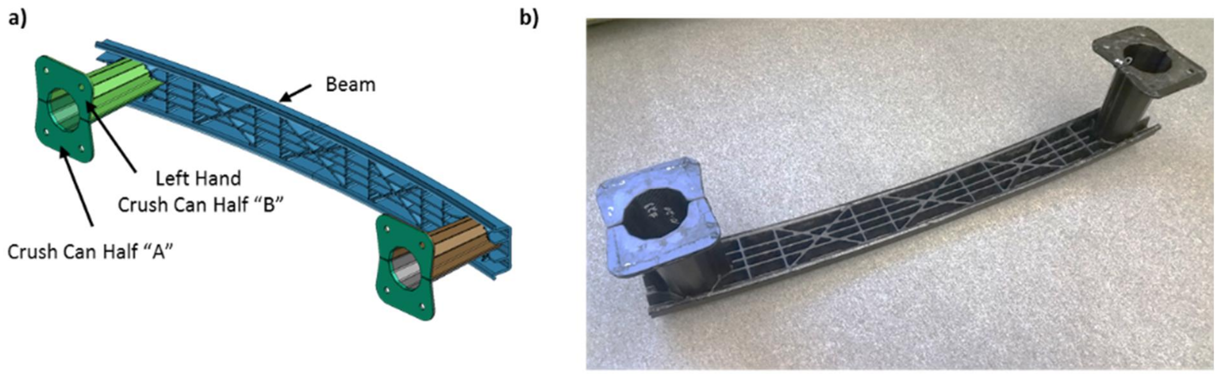

Figure 1: a) CAD image of the FBCC system. The main components are highlighted, including the beam, the right hand crush can (x2), and the left hand crush can (x2). b) Photograph of an assembled FBCC.

Material and Processing Selection

Material Selection

Two materials were used for the manufacture of the FBCC. The first was a woven carbon fiber/epoxy prepreg, which was used for the primary structural aspects of the FBCC. The second was a carbon fiber sheet molding compound (SMC), which had higher flow during molding to create complex architectures impossible to do with the prepreg alone. The SMC chosen 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 inch. The resin was an epoxy acrylate. According to the manufacturer, the tensile strength was 150 MPa, the modulus was 33 GPa, and the glass transition temperature was 130° C. The prepreg was composed of 2x2 twill woven Toray standard modulus carbon fiber with Cytec MTM 54FRB epoxy resin. The fabric was 343 gsm with 42% resin weight. This resin was chosen for its relatively fast curing time of 15 minutes at 140° C and ability to be demolded while still hot because of the high glass transition temperature generated during cure. Mechanical test results for the flat plaques molded from this prepreg are given in the next section.

Monotonic Coupon Testing

Monotonic coupon testing of the prepreg material was performed on four different layups: unidirectional (uni) fiber oriented $[0]_{4s}$, uni oriented $[0/90]_{2s}$, woven fiber (woven) oriented $[0/90]_{2s}$, and woven oriented in a quasi-isotropic $[0/45/-45/90]_{s}$. Plaques were molded using compression molding in a 610 x 610 mm tool. Testing results were used for developing material cards for the models, as well as for comparing the layups for the design of the FBCC. Tension tests followed ASTM D3039, compression followed ASTM D3410, shear followed ASTM D7078, and flexure followed ASTM D7264. Results from the tests are shown in Figure 2. In general, unidirectional fibers showed higher strength and modulus than woven fibers, but with lower elongation. Woven QI showed by far the best shear performance, due to the inclusion of ±45° fibers. Ultimately the woven QI layup was chosen for its relatively high elongation, good shear performance, and good performance in the closed-hat section testing discussed in the next section.

Closed-Hat Section Impact and Bending Testing

Further material/layup comparison was conducted by testing an “intermediate” structure. The intent of this testing was to evaluate a structure that was more complex than a flat plaque, used available tooling, and contained features similar to the final FBCC. The closed-hat section shown in Figure 3a,b was chosen for its similar curvatures to those found in both the crush can and bumper beam and the use of an adhesive joint for joining the two parts, similar to the crush can. Drop tower impact testing and four-point bend testing were used to compare layups. Three layups were compared, including “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 Mixed layup, layers 1, 2, 5, 10, and 11 were unidirectional fiber, while the rest were woven.

Figure 3c shows an image of the closed-hat section after a drop tower test. Results summarizing the testing are shown in Table 1. All tests were run from approximately the same height and with the same impact mass. Crush distance varied significantly from test to test with no significant differences apparent between the three layup. Plateau load was constant for each layup but varied from one layup to the next with QI woven showing the highest plateau load. Figure 4 shows an image of the four-point bend testing and the test results. Counter to the results from impact testing, the addition of unidirectional fibers improve the four-point bend strength of the closed-hat section. However, since the impact test is more similar to the loads experienced in the crash test and with input from the design/CAE team, we ultimately selected to use all woven material in a QI arrangement.

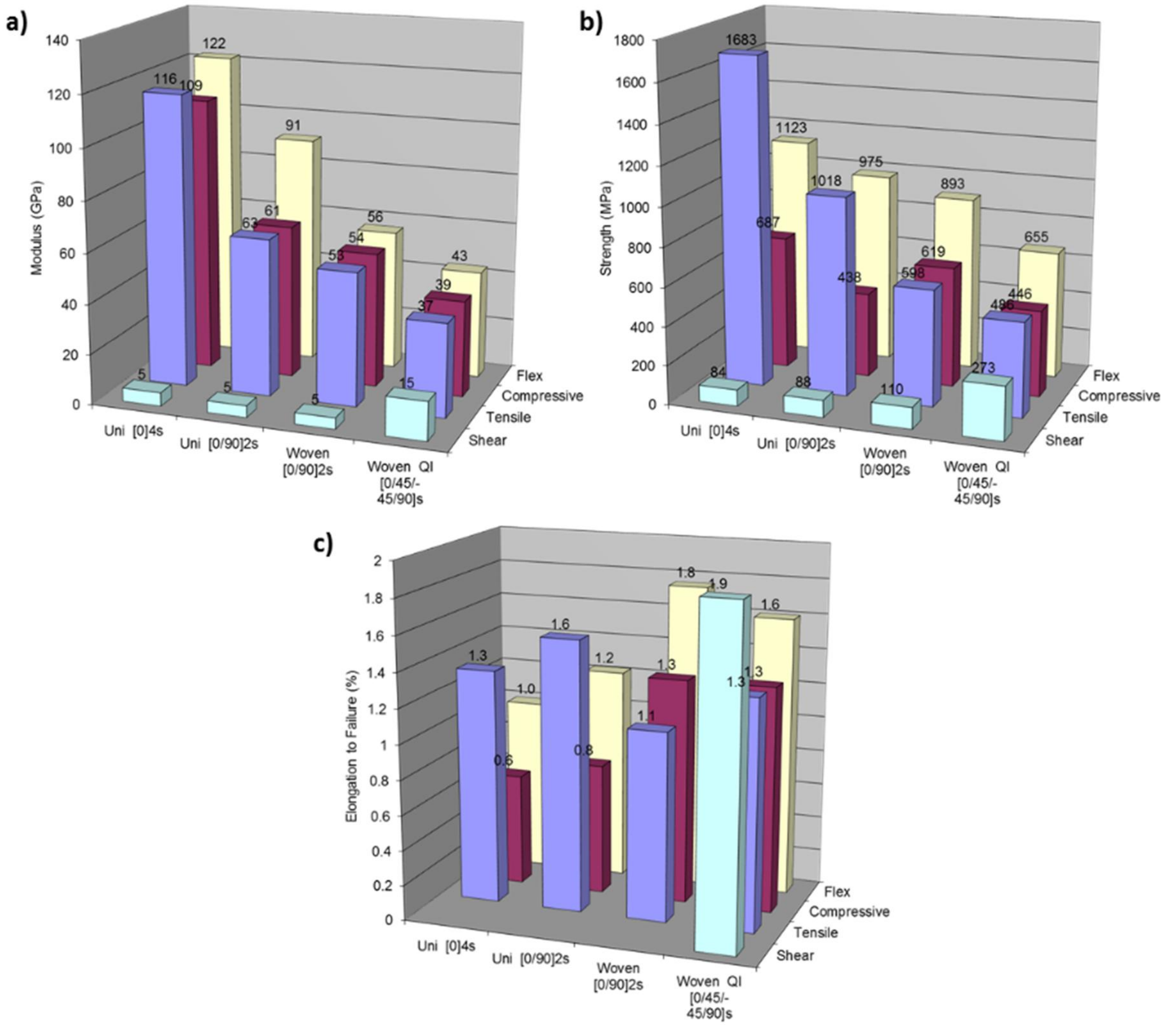

Figure 2: Monotonic coupon testing results for the prepreg in various layup configurations, including a) modulus, b) strength, and c) strain to failure.

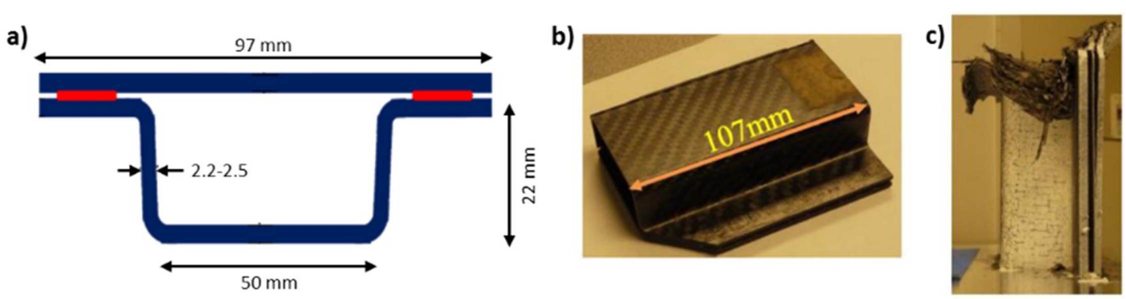

Figure 3: Images of the closed-hat section, including a) cross-sectional dimensions, b) a photograph of the structure ready for drop tower testing, and c) the structure after drop tower testing.

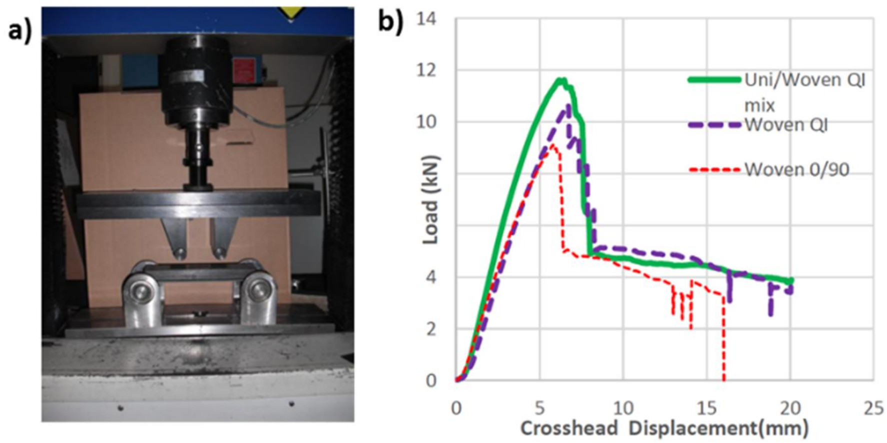

Figure 4: Four-point bend testing of the closed-hat section showing a) an image of the test and b) the test results.

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.

	QI Woven		0/90 Woven		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

Production of FBCCs for Crash Testing

FBCC Production Procedure

FBCC components were produced by compression molding using two-part tools. These tools were designed with 100 mm runoffs around the parts and used a shear edge to seal the mold cavity. The crush can tool is shown in Figure 5. Both components were molded using a combination of sheet molding compound (SMC) and continuous-fiber prepreg, co-molded and co-cured. 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 measured by mass prior to insertion. Both the beam and crush can tools were designed to allow for significant runoff. Excessive run-off was controlled by extending the prepreg exposure time to temperature in the mold (“pregel”) prior to application of pressure and localized use of SMC at the at the shear edges of the molds.

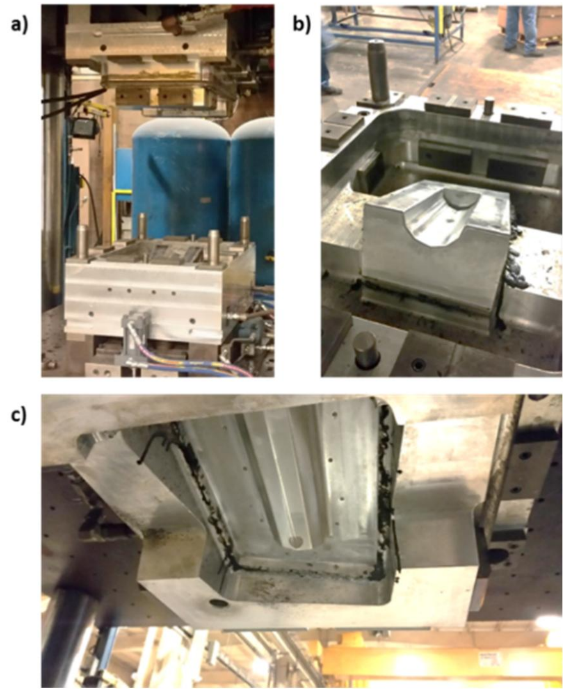

Figure 5: Images of the crush-can mold. A and B molds were mirror images of each other. a) The mold shown in the open state in the press. b) The lower half of the mold. c) The upper half of the mold.

The main crush can structure was composed of 12 layers of woven carbon fiber prepreg with a $[0/45/-45/0/45/0]_s$ stacking sequence. The nominal target thickness was 2.8 mm. Prior to molding, the prepreg was manually preformed in 2D then preformed to shape using dedicated forming tools. In these tools, spring loaded draw bars applied light pressure to the prepreg edges as the ply stacks were being preformed, preventing wrinkling. The preformed prepreg was then stored on a buck to maintain shape in a freezer until molding. A preformed prepreg pattern for the crush can is shown in Figure 6a. The flanges were molded from SMC inserted into the mold in the appropriate locations. Flow of the SMC allowed it to form the complex structures of the flanges. For the crush cans, glass fiber SMC was used instead of carbon fiber SMC, because of its better flow characteristics. The extreme tilt of the tool prevented sufficient pressure on the SMC to give appropriate flow of the carbon fiber charge. Below is a summary of the crush can molding procedure:

1. Prepreg layers are assembled in the specified orientation sequence and preformed to the final shape at room temperature.
2. SMC charges are cut to the approximate shape and the quantity is verified by mass.
3. The top mold is preheated to 143° C and the bottom to 137° C. Surfaces of the mold are pre-treated with mold release before every part.
4. The preformed prepreg is placed into the lower half of the mold. The mold is then covered with board insulation while the prepreg pre-gels. The pre-gel reduces flow and therefore run-off during molding.
5. The insulation is removed and the SMC is laid in the mold. The mold is then closed for 10 minutes while the part cures. Compression loads around 250-450 tons ensured excellent consolidation and porosity <1%.
6. The part is removed and the mold is prepared for the next part.

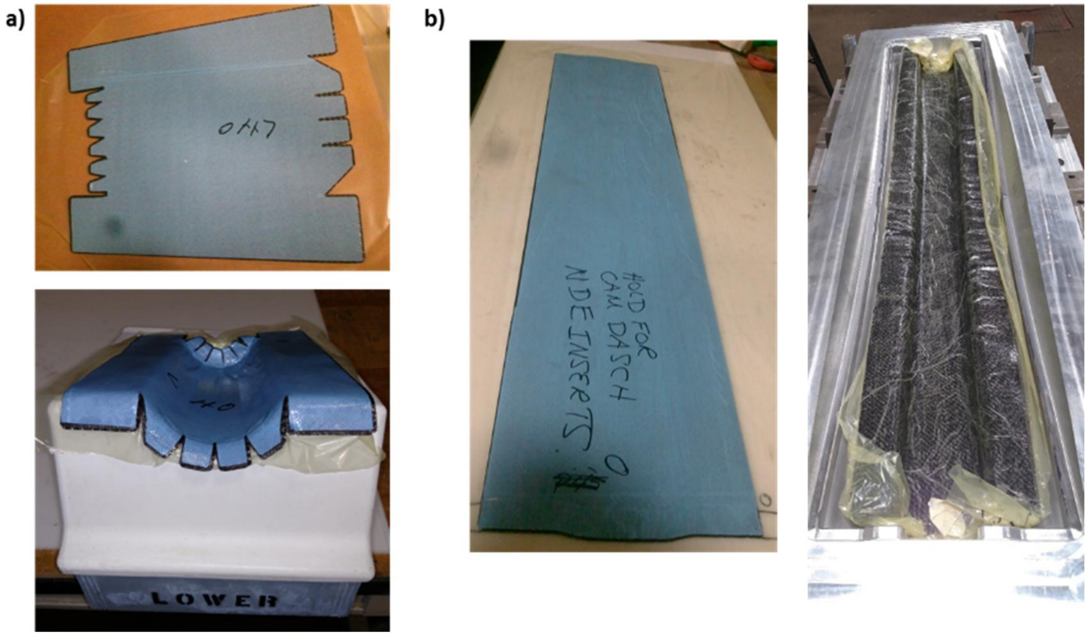

Figure 6: a) Image of a crush can half prepreg kit before (top) and after (bottom) preforming. b) Image of a bumper beam kit before (left) and after (right) preforming.

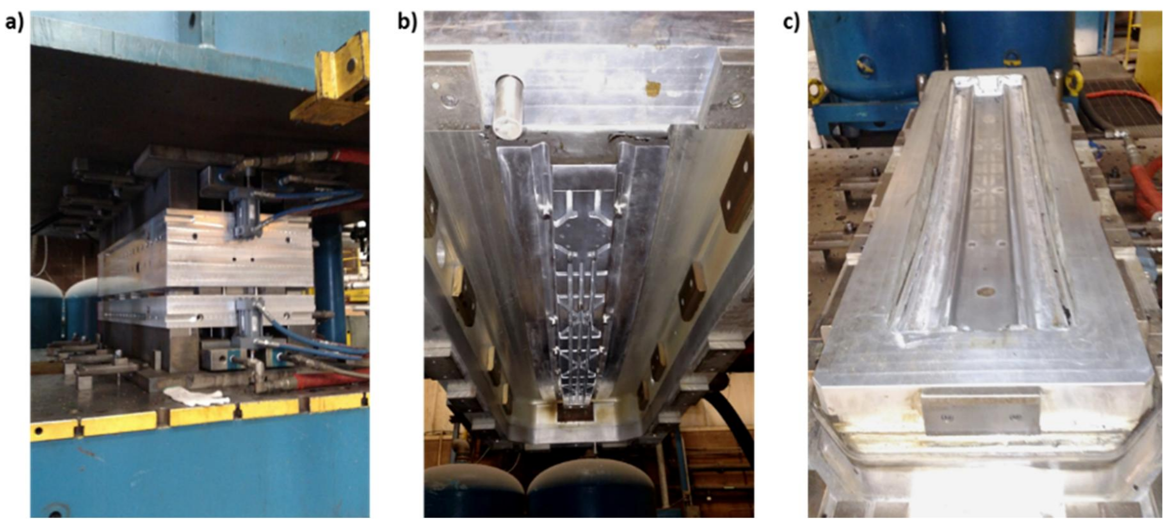

Figure 7: Images of the bumper beam mold. a) The mold shown in the closed state in the press. b) The upper half of the mold. c) The lower half of the mold.

The main beam structure was composed of 24 layers of the same prepreg with a $[0/45/-45/90/0/45/-45/90/0/45/-45/90]_s$ stacking sequence. The nominal target thickness was 5.6 mm. The beam was molded using the same procedure as for the crush cans except with a dwell time of 15 minutes. See Figure 6b for an image of the preformed beam. The carbon fiber SMC was placed in the mold after the pre-gel to form the ribs.

Following molding, the parts were trimmed to final dimensions using CNC milling. A five-axis mill was used for crush cans and a three-axis for the beams. Custom fixtures were designed to accurately hold the complex parts in place during trimming. During trimming of the crush cans, holes were drilled into the side flanges for rivets used as part of the joining process.

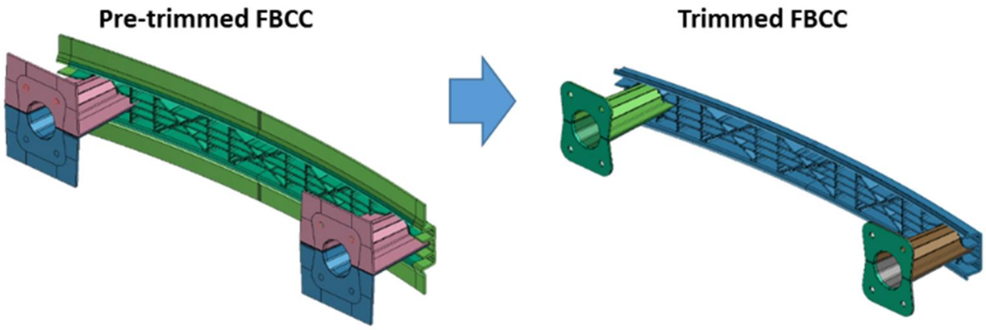

Figure 8: CAD image of the FBCC before and after trimming. Note that each component was trimmed separately prior to assembly.

After trimming, the parts were assembled into FBCCs using adhesive bonding and riveting. Each FBCC is composed of 1 bumper beam and 2 crush can sub-assemblies. See companion paper *Joining and Assembly System for Thermoset & Thermoplastic Composite Materials* [1] in this conference for further details on this process. The parts were primed with Dow BETASEAL 43532, then bonded with BETAFORCE 2850L. The adhesive to join the crush cans sub-assemblies was oven-cured while the halves were clamped together. The crush can-to-beam bonding was done in a custom fixture at room temperature.

Highlighted Processing Issues and Solutions

Excessive Resin Runoff

When initially designing the tooling, we wanted to ensure that the fabric did not impinge on the shear edges, thus damaging the shears. Thus, we were overly cautious in using 100 mm runoffs. This allowed us to have enough of a landing outside the vertical areas of the part to prevent the fabric collapsing into the vertical trough, while also keeping the fabric out of the shear edge. This was successfully demonstrated in the USAMP Structural Composites Underbody Project [3], with a faster curing resin. However, what was not foreseen was that this very large amount of runoff area would allow significantly more area for the resin to ooze out of the fabric when under pressure. At the advice of Cytec, the prepreg supplier, we instituted a pre-gel time of 3 minutes with no pressure to initiate resin cure. Strips of SMC were also added on the outside of the fabric area to act as dams to keep any flowing resin in the prepreg material.

Tool Wear and Draw Marks

Aluminum was chosen for the mold core and cavity for both crush can and bumper beam tools. While the aluminum tool held up well for the crush can molds, issues arose in the bumper beam mold after approximately 40 parts. Figure 9 shows that the small features used to form the ribs bent as a result of the large molding pressures and went out of draw. This became evident when scrapes (drag marks) appeared on the parts during demolding. A repair was attempted by re-machining the ribs to include the required draft angle. However, this repair was short lived and the problem reoccurred after about 10 beams.

There are two potential solutions to this issue. The first is to use steel for the mold core, which is significantly stiffer and stronger on a volumetric basis than aluminum and therefore less likely to bend under the same molding pressure. Of course, steel is also significantly heavier than aluminum, and more costly to machine. The second solution is to redesign the beam either without ribs, or such that the ribs do not require such small cantilever features in the mold.

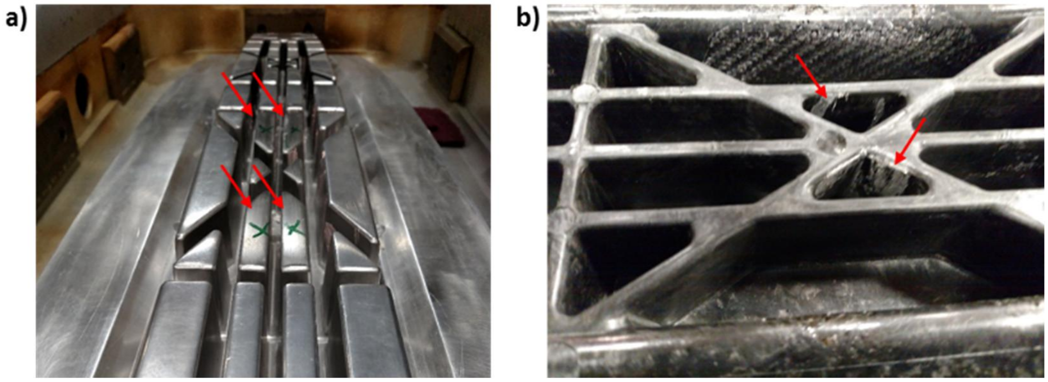

Figure 9: a) Misalignment of the mold core rib features arising after approximately 40 bumper beams. Features marked with a green "x" and red arrows are out of alignment. b) The resulting drag marks on the ribs of a bumper beam.

Reduced Material Properties Compared to Flat Plaques

During early crash testing trials, it appeared that the crush cans were not absorbing the energy that was predicted during the design stage. To explore the cause, we conducted mechanical testing on coupons cut from the facets on molded crush cans (Figure 10). One molded crush can assembly (two halves) was obtained to cut tensile and compression specimens. Six tensile specimens and eight compression specimens were tested at Ford Research Labs. NDE was conducted on the specimens prior to testing to ensure that no damage, such as delaminations or excessive voids, was present in the crush cans.

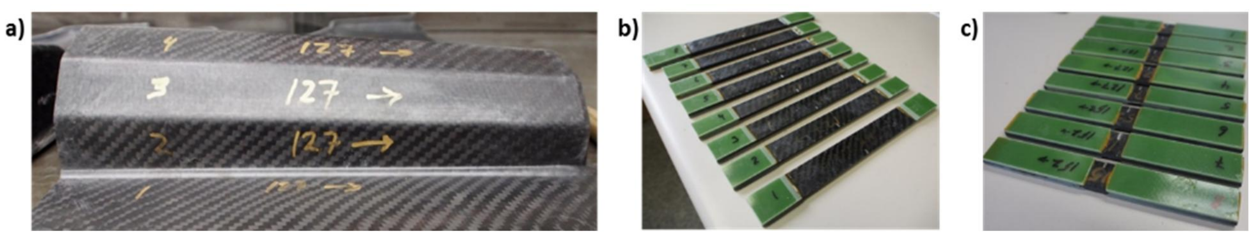

Figure 10: Coupons were cut from the flats of the crush can for mechanical testing. a) The crush can with the upper and lower flanges removed and future coupons labelled. b) Tensile coupons. c) Compression coupons

The specimens were cut on a wet-saw with diamond-coated circular blade. Widths for each specimen varied, dictated by the narrowest section and removal of any remaining radii. Facets selected were mixed to test all sides of both crush cans in tension and compression. After abrading the surface of the tab bonding area of the specimen and wiping with acetone, all specimens were tabbed with Garolite G-11 using 3M DP420 adhesive. Tensile tests were again performed according to ASTM D3039 and compression according to ASTM D3410.

Material properties for the crush can coupons are compared to those from flat plaques in Table 2. Both sets used the same prepreg and molding parameters. The only difference between the sets was the molded geometry. The crush can coupons show significantly reduced mechanical properties. In particular, the crush can coupon tensile strength was 32% lower and the compression strength was 22% lower than the strength of the flat plaques. The cause of this reduction in strength and modulus is most likely to be distortion/wrinkling of the fabric during molding. This misaligns fibers relative to their intended orientation. The results from NDE discussed in the next section further elucidate this phenomenon.

Table 2: Comparison of mechanical performance in tension and compression for coupons cut from crush cans vs. those cut from flat plaques. The materials and processes are the same in each case, and the only differing factor is the molded part geometry.

Test	Modulus (GPa)	Failure Stress (MPa)	Strain to Failure (%)
Compression Testing			
Crush Can Coupons	32.1 ± 2.9	348 ± 55	1.24 ± 0.24
Flat Plaque	38.5 ± 0.2	446 ± 27	1.29 ± 0.10
Tensile Testing			
Crush Can Coupons	32.4 ± 2.9	332 ± 93	0.89 ± 0.34
Flat Plaque	37.4 ± 0.2	486 ± 20	1.31 ± 0.07

Summary of Non-Destructive Evaluation Findings

NDE revealed several processing imperfections that were not initially apparent during molding. These issues would need to be resolved before a similar FBCC design could go into production but for the purposes of this paper are only identified. See companion report Non-Destructive Testing Throughout the Development of a Carbon-Fiber Composite Automotive Front-Bumper/Crash-Can Structure [4] in this conference for further details on this process.

The primary issue observed in the crush can arise from the complex molding condition where the SMC met the prepreg at the 90° bend at the base flange. As shown in Figure 6, the prepreg kit is designed to extend around this bend and interface with the SMC in the flange. Ideally, the SMC would be restricted to the flange and the prepreg weave would follow a perfect, off-the-roll twill pattern. However, Figure 11a shows that the SMC infiltrated around this bend and actually flowed up the face of the crush can. This is potentially beneficial if the interface between materials is improved. However, Figure 11b and Figure 11c show that the pressure of the flowing SMC resulted in severe distortion (wrinkling, bunching, and stretching) of the prepreg. This distortion, particularly as shown in Figure 11c, is likely the cause of reduced mechanical properties of the crush cans compared to the flat plaques.

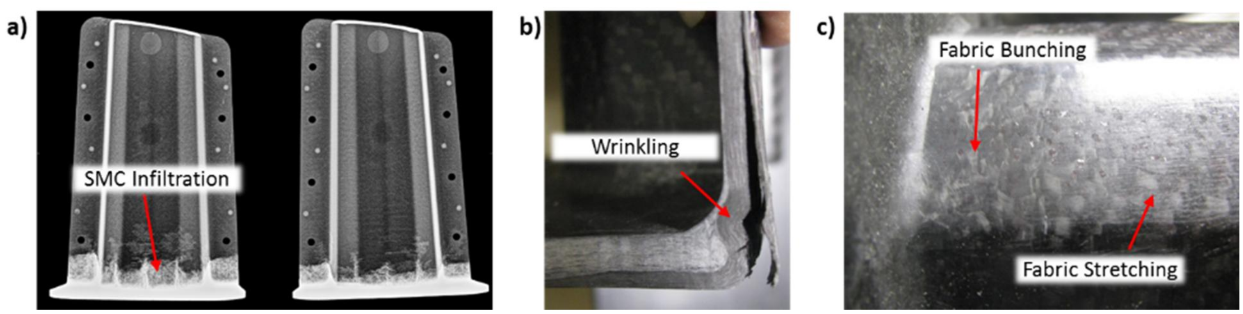

Figure 11: a) A radiograph of two crush can halves showing the SMC infiltration onto the surface of the prepreg. The prepreg appears as the darker material while the SMC appears lighter. b) Wrinkling of the prepreg at the base of the crush can. c) Fabric stretching and bunching on the face of the crush can due to flowing of the SMC from the bottom flange.

The intricate geometry and complex molding condition of co-molding SMC and prepreg also resulted in imperfections in the bumper beam. Figure 12 shows cross-sections and CT scans of the bumper highlighting these imperfections. In the ribs, significant cracking and porosity was evident. Cracks and wrinkling at the interface of the materials likely resulted from insufficient molding pressure or air entrapment.

The crush cans and beams could be improved through further refinement of the mold tooling geometry as well as the materials themselves. Tailoring of the rheological and curing properties of the SMC and prepreg, and improvement of the mold design to optimize pressure distribution are particularly important.

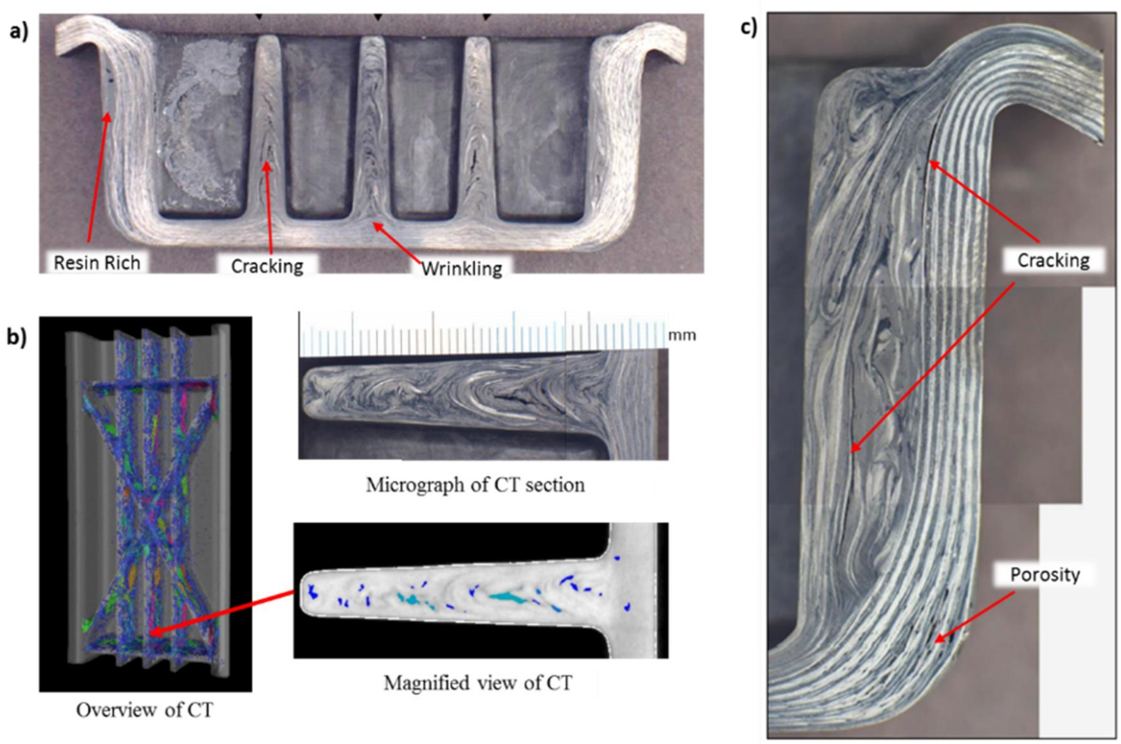

Figure 12: a) Photograph of a cross-section of the bumper beam with several imperfections marked. b) CT images and associated photograph showing porosity in the ribs of the bumper beam. Colors denote the size of porosity with blue corresponding to small pores and red to large pores. c) Micrograph showing cracking and porosity where the SMC ribs meet the interior of the beam fabric.

Summary and Conclusions

In this portion of the VMM project, we developed a manufacturing process and then produced parts for crash testing of the front-bumper crush can system. This included selection of materials and measurement of material properties that were then passed onto the design/CAE team for designing and predicting performance of the FBCC. While more than 50 FBCCs were successfully produced using this method, areas for improvement were identified. Current material technologies available would enable the reduction of molding time from 10-20 minutes down to 2-3 minutes or less by using new “snap-curing” resin systems. This reduction would be a key for an actual production-intended part. Significant defects, including fiber distortion and internal cracking/porosity, were identified in the molded materials using NDE. Improvement to mold design, preform design, and changes in material selection could potentially eliminate many of these issues. Manufacturing is a key consideration in the development of models for predicting composite behavior in crash events. The realities and challenges of the molding operation result in imperfect parts containing defects. These defects need to be predicted and integrated into the structural models to obtain accurate predictions.

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