D. Automotive Composites Consortium Focal Project 3 Composite-Intensive Body Structures (ACC 080[i])

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Objectives

- Design, analyze, and develop the technology to build a composite-intensive, body-in-white (BIW), offering a minimum of 60% weight savings over steel at a cost close to that of steel, while meeting manufacturing, assembly, and performance targets.
- Provide a focus for bringing together technology developed by each of the Automotive Composites Consortium (ACC) working groups through emphasis on carbon-fiber-reinforced composites and the use of hybrid materials, faster manufacturing processes, design optimization including crashworthiness, and rapid joining methods.

Approach

- Optimize the design and complete the finite element analysis (FEA) for the carbon-fiber-composite BIW (Phase 1).
- Build one part of the BIW (the B-pillar portion of the body-side) to demonstrate high-volume processing methods (Phase 2).
- Develop and model a structural test for the B-pillar.

Accomplishments

- B-pillar preforming pattern for the Hexcel 12x3K carbon-fiber was developed.
- Carbon-fiber-reinforced B-pillars have been preformed, molded, and bonded.
- Flow modeling studies for the full body-side model with carbon-fiber were completed for multiple injection ports.
- Several new ACC programs being bubbled up for potential full-fledged projects

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Introduction

The ACC Focal Project 3 (FP3) is intended to be a design and processing study to develop a cost-effective manufacturing scenario for carbon-fiber-intensive composite vehicle structures. All of the materials, manufacturing processes, and fabrication and assembly methods to be considered in this project are to be consistent with the following overall objectives:

- High-volume production techniques (>100,000 units per year)
- Cost parity with equivalent steel structures
- Overall 60% mass reduction relative to steel BIW structure
- Structural performance equivalent to or better than that of a steel structure
- Dimensional tolerance equal to or better than that of steel

The current stage of the project is the development of the manufacturing processes necessary to produce the body side. This work was done with the B-pillar (a portion of the FP3 body-side design shown in Figure 1) preform and molding tooling. The preliminary preform development with glass fiber was completed earlier. The preforming and molding trials with carbon fiber are now also completed. A run of carbon-fiber B-pillars has been prepared for bonding and structural testing. The structural reaction-injection molded (SRIM) injection/compression mold-filling model was extended to multiple injection ports.

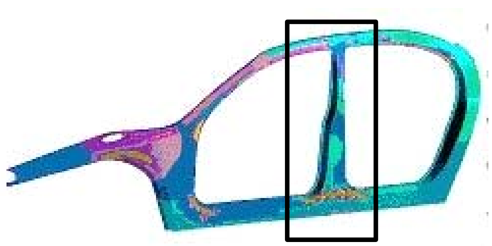

Figure 1. B-pillar portion of body side is outlined.

New Program Bubble-up

Several new efforts are in preliminary development as potential new focal projects, and brief summaries of each will be given.

- Bond-line read-through
- Structural-composite underbody
- Lightweight, low-cost composite seat

B-Pillar Preforming Development

Final preforming development efforts were completed on the ACC P4 (see 4.A) machine using the original B-pillar preform tooling. Previous preforming efforts were conducted using revised tooling in which the 'B' surface is the preform deposition surface and the 'A' surface is the consolidation surface. Although the preform and molding tool compatibility issue was addressed with the revised preform tooling, the inverse orientation of the deposition surface (relative to the original tooling) created additional issues during the material deposition process, which turned out to be more intractable than the original reason for changing the tooling.

The preforming optimization proceeded with many delays due to servo errors, robot-cabling problems, a fiberglass type change (which altered deposition patterns) and issues involving the SRIM molding press. However, the necessary maintenance was performed and preform development was resumed. The type of glass fiber used for the pre-carbon optimization was changed to Owens Corning (OC) 905 from OC 433. The 905 has a slightly different sizing applied, causing it to spray differently. This difference in sizing led to further modifications of programs already made specifically for the type 433 glass. The SRIM molding press, which provided molding performance feedback to the preforming process, was also down for maintenance. However, the issues were resolved and molding has commenced.

After completion of optimization with glass fibers, the decision was made to manufacture carbon-fiber preforms once an overall fiber volume fraction of 40% was achieved with glass fibers and at least a few preforms could be successfully molded. While the latest programs were modified to optimize the spraying of glass fibers, further modifications to the programs were made once the material was changed to carbon fiber.

Since a commercial-grade, low-cost carbon fiber was not available at this stage of the program, the Hexcel 12x3K fiber used in the earlier plaque program was used for the B-pillar preforms. Overall, the target fiber volume fraction of 40 % was achieved using carbon-fiber; however, difficulty in molding completely- filled carbon-fiber preforms at this fiber volume fraction led to molding preforms with only 35 % overall fiber volume fraction for most of the final test pieces.

The Hexcel 12x3K roving is not a regular production material, and thus issues with the carbon-fiber spools were encountered, such as knots which get clogged in the feed tubes and variations in density. Both are possibly due to inconsistencies in sizing application. A large amount of carbon fiber was wasted due to the knots interrupting the deposition routines.

Extensive areal-density sampling was performed on one set of B-pillar inner and outer preforms. The sampling was accomplished with 25 mm or smaller cutouts, which exacerbates the variation in fiber density measurement. The data from these two preforms indicate high variability of fiber volume. An example is given in Figure 2, which shows the fiber content in the different regions of the outer preform. The shallower inner preform was easier to produce and had a lower fiber variation across the part.

Even though the preforms were not fully optimized, a run of carbon-fiber preforms was made with the current process capability. Figure 3 shows carbon-fiber preforms ready for molding. Issues with the carbon-fiber spools, such as knots and variability in sizing, continued to be an ongoing problem. Also, cycle times could be further reduced as current total cycle times for inner and outer B-pillars remain

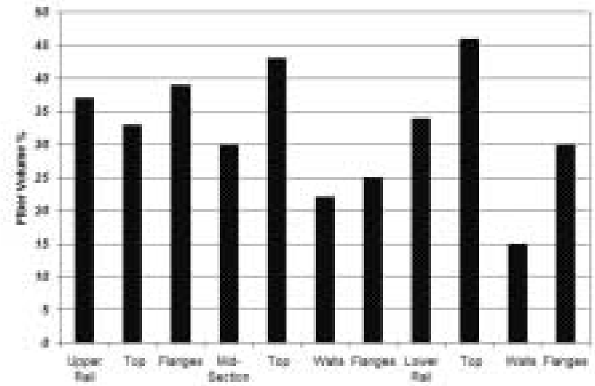

Figure 2. Variation in fiber volume across different regions of the B-pillar outer preform.

Figure 3. Carbon-fiber B-pillar preform, outer and inner views.

at 6 min. 34s and 8min. 35s, respectively. The total fiber spraying times are 3min. 30s and 5min. 47s for inner and outer B-pillar routines, respectively.

B-Pillar Molding Development

The preliminary preforming and molding development work with the glass preforms was a prolonged activity since both the preforming and molding were difficult processing conditions due to the complicated part geometry. There was also a limited supply of the carbon fiber, so it was deemed necessary to have processing conditions as well defined as possible with glass before changing to carbon. The difficulty in processing the available carbon fiber was discussed above. The combined factors of the limited personnel available for preforming and the poor yield of preforms meant that there was only a limited amount of additional preform development with the carbon fiber. The preforms were not perfect, but were deemed satisfactory for molding. Figure 4 shows carbon-fiber preforms in the molding tool.

Figure 4. Carbon-fiber B-pillar preforms in the SRIM mold.

Preliminary molding runs indicated that there was better success in molding preforms at 35 volume % than at 40%. It was decided that most of the program objectives could be demonstrated with the 35% preforms and to not consume the additional resources that would have been necessary to complete the 40% preform development. The completed B-pillar inner and outer panels are shown in Figure 5.

Even with the 35% preforms, it was necessary to go to maximum press tonnage, 1000 tons, to completely fill the parts. This tonnage was necessary to get the resin to the far ends of the parts. There were occasional small dry areas where the variability in fiber deposition caused areas of low permeability in the preforms. These were primarily in the thicker rail sections. These observations are consistent with the fiber distribution data that show the preforms to be heavy on the flat areas and lighter on the walls and flanges. Thus, most of the resin flow is through the heavier portion of the preform. This also indicates that, with a more uniform fiber distribution, this part should fill at 40% fiber volume. A part of the complexity and long narrow aspect ratio of the B-pillar would probably require a flow leader, a runner cut into the mold cavity surface, to assist resin flow to desired areas.

The B-pillar has demonstrated a number of issues to consider were this effort to continue to full body-side. In addition to the flow leader, the injection points should be in the thicker sections of the part. This would reduce the amount of resin that has to flow through constricted areas of the preform. With the B-pillar there was only a limited choice of where to position the injection point. The full body side would have more flexibility in selecting injection-port locations. The flow modeling, discussed below, addresses molding the full body side. Also, the resin seals around the cavity must be designed in such a way that they do not hinder removing the molded part from the tool.

Figure 5. Molded carbon-fiber B-pillar.

B-Pillar Bonding

Bonded assemblies were fabricated to be tested and provide experimental data to validate the structural models created in this project.

Bonding of B-pillar inner and outer panels preformed and molded using carbon-fibers was completed at EMC^2 in Sterling Heights, MI. Two sets of panels were bonded first to confirm the bonding parameters. Six sets were then bonded for subsequent torsion and bending tests. A bonded assembly of carbon-fiber B-pillars is shown in Figure 6.

Figure 6. Carbon-fiber assembly in heated bonding fixture.

All six bonded parts were coordinate-measuring-machine (CMM) checked after bonding in 32 locations along the bond-line and 23 locations on the outer surface. One part fell within the dimensional tolerance (±1.0mm) in all locations. The locations that fell outside of the specified tolerance on the other parts were primarily along the center of the B-pillar and were slightly outboard of design intent.

Flow Modeling

Professor Suresh Advani of the University of Delaware developed a flow model for the molding of carbon-fiber preforms by the injection-compression process used in FP3 (see also 4.L). The flow model is a design tool to assist in optimizing the location of the injection points for body-side tooling. The intention was to develop and confirm a flow model with the B-pillar and then extend it to the full body side. The body-side flow model was completed earlier for a single injection point, and is now extended to multiple injection points.

The mold filling of the full body side was modeled in a similar fashion to the B-pillar. At the start of the injection step, the mold is assumed to be partially open, with a gap between the preform and the upper mold half. The resin is injected into this gap and is initially pooled on top of the preform. In the compression step, the mold is fully closed, which then forces the resin completely through the preform, filling out the part.

The filling dynamics, including the last area to fill and the cavity pressure, were modeled for several locations of multiple injection points. This was not an optimization, since with the decision to not produce the full bodyside, there was no justification for a large expenditure of resources for a rigorous optimization. Instead, several case studies were presented to show the effect of using different injection points. An example of the case study is shown in Figure 7 above. The upper chart shows the filling profile with three injection points marked by the arrows. The adjoining dark areas indicate the initial resin pools, and the circles show the last points to fill. The lower chart is the corresponding pressure prediction, with the circle indicating the

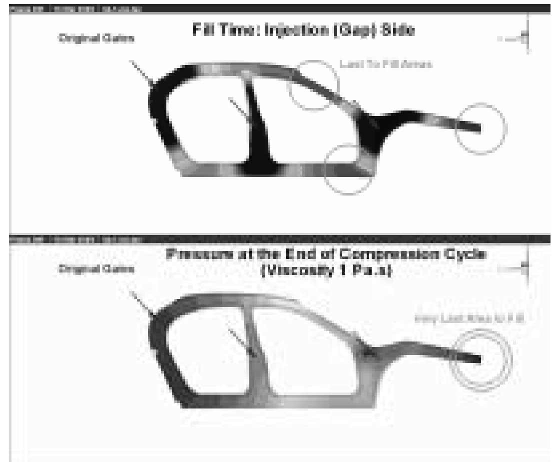

Figure 7. Mold-filling model case study; arrows indicate resin ports, circles are last-to-fill areas, and double circle is lowest-pressure area at fill completion.

position of the lowest pressure in the cavity at completion of fill.

Biocomposites and slurry preforms

Another focus area for reducing vehicle mass is biocomposites. Biocomposites encompass both natural fibers for reinforcement, and using resins based fully or partly on natural products.

One of the major challenges of working with natural fibers is that processing the fibers into composites, either fully formulated or as preforms for liquid molding, is not developed in a cost-effective manner that will yield the volumes needed for automotive production. We are working with Materials Innovation Technologies, Hendersonville, NC, and Advanced Process Technology, Columbia City, IN, to evaluate a slurry process for making preforms. This slurry process is currently used to make speaker cones for audio systems, and is well developed for the uniformity and process speed necessary for that market. The requirements for the automotive market, however, require different fibers, as well as much heavier preforms.

We have evaluated preforms made of carbon-fiber, glass fiber and hemp fiber with this technology, and have found it to be promising. This provides an alternate process for our current fibers, and means for processing fibers which cannot pass through the P4 system. A recent molding trial used commercial urethane resin, as well as a soy-based resin. Processing was successful, in spite of initial concerns about permeability. Material property evaluation is underway.

B-Pillar Summary

The successful preforming and molding of carbon-fiber B-pillars has been demonstrated. The injection/compression mold-filling model is completed and an alternative preforming technology was investigated. The carbon-fiber distribution by the P4 process is not yet at the uniformity needed for production, but the process feasibility has been demonstrated. The carbon-composite B-pillars were successfully bonded, and these assemblies will be subjected to structural testing shortly. Even though the demonstration batch was molded at 35% fiber volume, much of the resin flow was actually through sections of preform which were above 40% fiber volume. Thus, with improved fiber uniformity, it is expected that preforms of 40% fiber volume would be successfully molded.

Bond-Line Read-Through

A new effort was established to develop a tool to predict bond-line read-through (BLRT) in adhesively-bonded joints was established in FY 2006. This effort consists of three phases:

- Phase 1: Identify a measurement tool capable of objectively quantifying the severity of BLRT
- Phase 2: Experimental evaluation of the contribution of various factors on the creation of BLRT
- Phase 3: Development of an analytical tool to predict BLRT during the design phase.

A better understanding of this defect will allow OEMs to establish minimum material gage specifications based on structural criteria rather than on appearance criteria.

Phase 1

Four imaging systems with the potential to provide the needed objective data for quantifying BLRT were identified. Three of these systems were "structured light" systems. One was a laser scanning system. A preliminary evaluation of each was conducted and the Ondulo system from Visuol Technologies, Metz, France was found to be the most promising. Consequently, this system was selected for a more in-depth evaluation.

For the in-depth evaluation of the Ondulo system, Meridian Automotive Systems provided a number of decklid assemblies that the plant felt exhibited varying amounts of read-through. The entire decklid was primed and then cut in half. One half of each decklid was painted with a black basecoat/clear-coat automotive paint system. The ACC Joining team visually evaluated these parts prior to the Ondulo trial and found it very difficult to see any defects. Nevertheless, four painted decklid halves and two primed decklid halves were selected for evaluation with the system.

This evaluation showed that the Ondulo system was able to image BLRT below the visible limit. This is a positive result since it will allow the team to identify what factors contribute to the creation of BLRT even if the contribution cannot be seen with the unaided eye. Example of Ondulo image is shown in Figure 8.

Unfortunately, the methodologies normally used to quantify defects in this system resulted in numerical values that did not correlate to the team's visual assessment of the severity of the defect in the images.

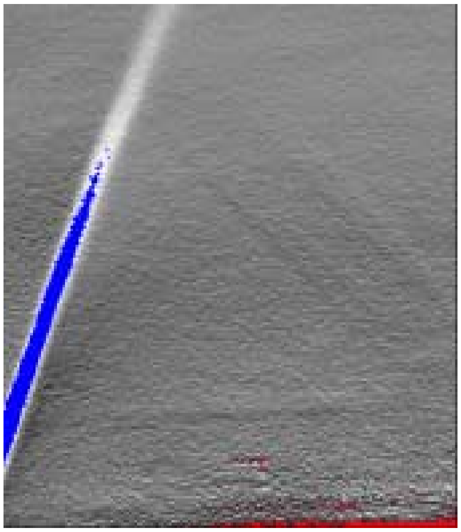

Figure 8. Curvaturemap for primed decklid #3.

A second trial was completed at Meridian Automotive System's Shelbyville, IN manufacturing plant with the intent of creating parts with more visible defects on the parts. Defects were visible in these parts, but not until after the bonded parts had been primed. Even though the severity of the defects was greater and the difference between the severities of the defects was greater, the existing methods for quantifying defects still did not produce values that corresponded with our visual assessment.

Visuol Technologies was then contracted to identify an appropriate metric given the data available in the images. The Joining team created a set of fifty panels that cover the spectrum of BLRT severity from not visible to very visible. The set included "as-bonded", primed, and painted panels. The images of these panels will be used to derive the parameters that influence the apparent severity of the defect.

BLRT was visible on the primed plaques and the painted black plaques. Those two sets of panels were visually ranked by thirty people to provide baseline "visual assessment" data. The imaging and analysis of those images will be completed in FY 2007.

Phase 2

Once a measurement tool is available to quantify the severity of BLRT, experiments can be completed to determine the root causes of this defect. The team generated a list of forty-one potential sources of BLRT. The list was then reduced by designating certain factors as noise factors and by prioritizing the list. The team discussed how best to evaluate the effect of the various factors. A flat outer panel was determined to be sufficient for this work, but no existing inner-panel tool was found that meets the project's needs. Consequently, a project-specific inner-panel tool was designed. The construction of the inner-panel tool was contracted to JATCO Machine & Tool Co., Inc in Pittsburgh, PA after a competitive bidding process. The tool construction is now underway.

Structural Composite Underbody

A new effort being developed to take advantage of the learnings from FP3 is the structural composite underbody. The objective is the design, analysis, and fabrication of a structural-composite underbody, as well as the joining of this underbody to the rest of the vehicle. This is targeted to be part of the USAMP Multi-Material Vehicle (MMV) project, and will follow the MMV goals for cost and mass as they are established. The primary research outcomes of this project will be:

- A 2 ½ minute cycle time (100k upa, 2-shift operation)
- Developing methods of joining and assembly of the underbody to the vehicle

A large, rear-wheel-drive vehicle has been selected as the donor vehicle for the MMV, including this underbody. Phase 1 of this effort is the selection of the materials and processes for the underbody. This involves:

- the development of a design concept, including a means of joining and assembly
- the preliminary design of the concept using a limited number of material and process systems
- the selection of a material and process system based on
  - manufacturing considerations
    - Is there a way forward to get to 2 ½ minute cycle time?
    - Is joining and assembly feasible in a manufacturing environment?
  - compatibility with MMV goals, including mass and cost
  - technical cost model analysis

Phase 2 will be full design, incorporating other components of the MMV, based on the donor vehicle.

Phase 3 will be fabrication of the underbody and assembly to the donor-vehicle structure.

Phase 1 had progressed with analysis of the current steel underbody, and selection of a design concept. This preliminary design is shown in Figure 9. This design concept makes use of ribbed sections, and will address attachment via weld-bonding to the front and side rails. Our analysis is now showing that strain will be a major factor in the performance of a composite material in this application, so we are developing an experimental program aimed at increasing the strain of our material options. This will target design of fabric reinforcements, as well as alternative fibers such as Kevlar or Spectra.

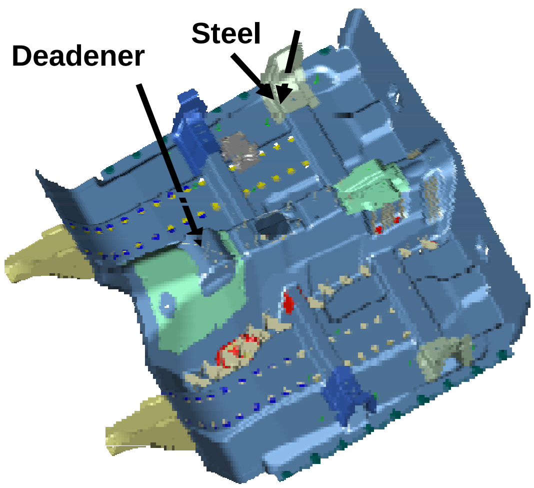

Figure 9. Top view of the preliminary design concept for the composite underbody.

Lightweight, Low-Cost Composite Seat

This is a new effort started in January of 2006. The primary objective is to develop materials, processes and designs to yield a light-weight, low-cost composite seat structure. A team has been established and a set of assumptions has been created.

On a vehicle level, 2^{nd}-row, outboard, stand-alone seats are the target applications for the composite. Comparator seats from each of the OEMs have been selected: Land Rover LR3, Chrysler Town & Country Stow N Go, and the GMT-800 (Suburban). Manufacturing volumes of up to 200k upa will be designed for.

On a structural level, only the back frame, cushion frame, and the pivoting recline/folding joint will be included in the scope of the effort. The structure will include provisions for mounting a conventional carry-over headrest and will be designed for inclusion of a seat-integrated restraint. The mechanisms and stanchions that mount the seat to the floorpan of the vehicle will not be included. These components are quite vehicle specific due to the variations in floorpan geometry and in desired articulation of the seats for fold-flat and easy entry.

On a materials level, the effort will investigate predominately glass-fiber-reinforced composites due to cost considerations, but will consider local reinforcement with carbon-fiber and other materials including metal reinforcements. Both thermoset and thermoplastic matrix material will be included.

This effort intends to further the understanding and state of research in several areas. In the design arena, it will seek additional parts- integration opportunities by investigating structural-appearance composites. Opportunities exist in folding seats since the seat back becomes a load floor in the folded position. This load floor is very often trimmed with an additional panel over the structural seat-back that provides both an acceptable appearance as well as abrasion and wear resistance. The goal is to integrate the appearance, wear, and abrasion resistance into the structural seat-back, thus eliminating pieces. There is also opportunity to integrate many of the current plastic trim covers into the structure of the seat.

Hard-point design will also be advanced. The pivoting joint between the seat-back and the cushion will require the use of a steel recliner mechanism and will need to be a bolted connection for trimming, assembly and repair. This will require innovative design of the bolted joints in the composite structures due to the high loads that these joints must carry, particularly when the seat-integrated restraint is included.

In the materials arena, the use of oriented fibers for local reinforcement will need to be developed at the high volumes required for the seat application. Hybrid materials of glass and carbon-fiber reinforcement with also need to be developed.

Comparison seat teardowns and testing have been have been preformed by MSX International, Auburn Hills, MI. As an example of non-destructive load testing, Figure 10, details the first static load case

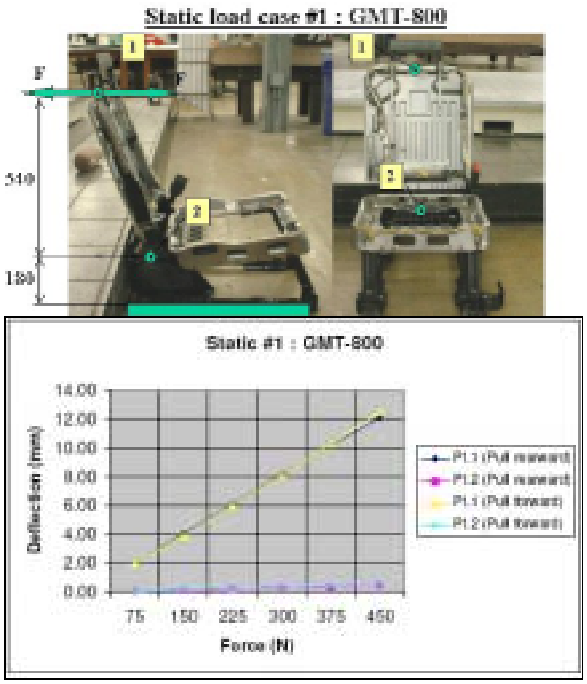

Figure 10. Test setup and example data from comparator seat testing.

where a series of loads were applied to the seat-back and deflections were measured at the top and bottom of the GMT-800 (Suburban) seat-back. Altair Engineering, Troy, MI, applied these load cases to the current seat design, Figure 11, generated by Chelexa Design, Taylor, MI. Three materials, a carbon-fiber composite, a long-glass polypropylene and a glass-fiber SMC, at a uniform thickness of 5 mm, were compared to the load case results, with the carbon-fiber composite being too stiff and the glass-fiber SMC and long-glass polypropylene not stiff enough. The seat design is being modified by Chelexa Design for each of the three materials to obtain the best weight savings.

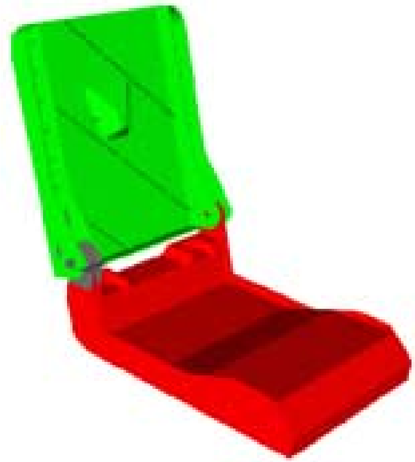

Figure 11. Design status of composite seat structure.

Publications

Stanley Iobst, Xinran Xiao, Libby Berger, Jeff Dahl, and Dan Houston, "Fabrication and Structural Modeling of the Automotive Composites Consortium B-Pillar," presented at SAMPE, Long Beach, May 4, 2006.

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[i] Denotes project 080 of the Automotive Composites Consortium (ACC), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.