D. Automotive Composites Consortium Focal Project 3 Composite-Intensive Body Structure

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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 for the carbon-fiber composite BIW (Phase 1 - completed).
- 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

- Initial preforming, molding, and bonding development of glass-fiber-reinforced B-pillar is completed.
- The final optimization of B-pillar preforming and molding is being completed with glass prior to the carbon-fiber work.
- Fixtures for the B-pillar 3-point bend and torsion tests were designed and built.
- Verified the B-pillar structural testing protocol with glass reinforced inners, outers, and bonded assemblies.

- A predictive model for B-Pillar test modes was completed
- Flow modeling studies for the carbon-fiber B-pillar and the full body side were completed

Introduction

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

We continue to develop the manufacturing processes necessary to demonstrate the body side. Preforming and molding trials continue with the B-pillar tools. Other major activities during this period were the structural testing and modeling of the B-pillar. An injection/ compression mold-filling model was also developed. In addition, a series of carbon-fiber plaques were molded as part of the carbon-fiber development program.

Program Redirection

It became apparent at the beginning of the year that insufficient resources were available within the FP3 program to generate the necessary matching funds to support the full body-side tooling and molding program. It was decided that the B-pillar portion of the body side, illustrated in Figure 1, would be the preforming and molding demonstration project for the Focal Project 3 program. Concurrent with the change in the program scope, the program leadership passed from Nancy Johnson to Stanley Iobst.

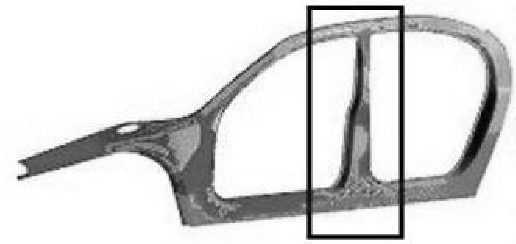


Figure 1. B-pillar section of body side structure.

The ACC is formulating other material and process programs, and it is likely that some of these processes will be demonstrated with the FP3 B-pillar mold. The resources released from the FP3 program are being redirected into the other programs within the ACC Processing Group, and there is actually an increase in the ACC membership to support these new programs.

B-Pillar Preforming Development

In support of FP3, preforming process development has been conducted to facilitate manufacture of B-pillar inner and outer preforms.

Experimental Preforming

Preforming development efforts were performed on the ACC/DOE preforming machine using the revised B-pillar preforming tooling. In the revised Gen-2 tooling, the 'B' surface is the preform deposition surface and the 'A' surface is the consolidation surface. Although the preform and molding tool compatibility issue has been addressed with the revised preform tooling, the inverse orientation of the deposition surface (relative to the original tooling) has created additional issues during the material deposition process.

High fiber density exists in 1.5 mm regions, mainly the flange regions, immediately adjacent to thicker (3, 4, 6, 8 mm) and subsequently higher fiber content sections of the component. A particular region exhibiting this issue on the B-pillar outer preform is shown is Figure 2.

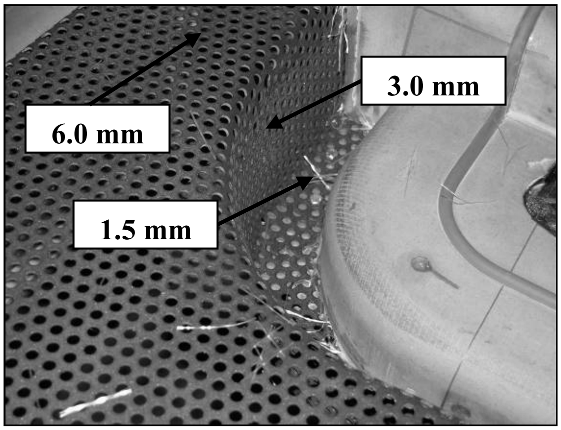


Figure 2. B-pillar outer preform region exhibiting material distribution issues in the 1.5 mm area.

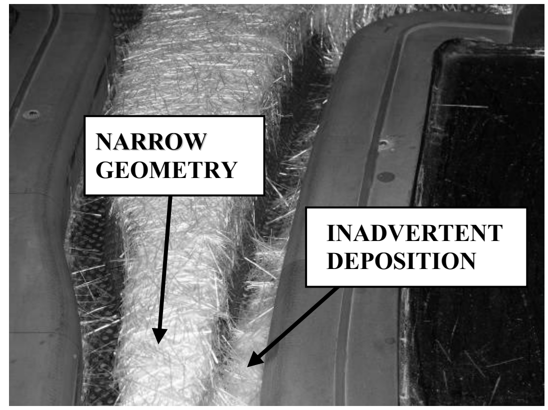


Figure 3. Inadvertent material deposition in 1.5 mm region (B-pillar outer).

This issue is more evident on the B-pillar outer preform; however similar issues also exist on the B-pillar inner in the inverted tooling condition. Despite extensive robotic programming efforts on both the B-pillar outer and inner preforms to alter the robotic positions and path, this issue could not be remedied. Areal density sampling data indicated fiber volume fractions far exceeding the specified fiber volume fraction of 40% even though fiber deposition routines for these regions were deleted from the overall robotic preforming program. A majority of the excess material is deposited in these regions during deposition routines associated with other sections of the component, unrelated to the 1.5 mm flange section (Figure 3).

This is exacerbated depending upon the thickness requirement and part geometry for a region in close proximity to the 1.5 mm regions. For example, narrow part geometries relative to the material deposition pattern will yield higher material concentrations in the associated flange section as the material is inadvertently projected to these regions due to the part geometry (Figure 2). When incorporating the deleted fiber deposition routines for the aforementioned sections of the B-pillar, areal density sampling data suggest greater than 100% by volume for the target fiber volume fraction of 40% at a 1.5 mm thickness.

In an attempt to improve material distribution, additional experiments were conducted via modifications to preforming process variables other than the robotic positions and path. Fiber length, tool center point (TCP) distance, and air velocity through the screen were identified as important preforming process variables. Although material distribution improvements were made through modifications to the above process variables, the magnitude was insufficient to improve conditions in the molded component. This was evident in subsequent molding trials where both fiber wash (insufficient material) and dry spots (excessive material) were still present despite extensive experimental preforming efforts.

Preforming Conclusions

Despite experimental preforming efforts using the revised B-pillar preform tooling, a fully optimized preform has not yet been realized. This may be attributed to a myriad of previously mentioned issues, all leading to inadequate material distribution within the preform. After making insufficient preforming progress with the revised screens, preform development reverted to the original screens.

Based upon the experimental preforming conducted to date on both the original and revised preform tooling, a 1.5 mm part thickness at a fiber volume fraction of 40% may not be feasible and possibly beyond the current process capability. Focal Project 3 B-pillar preforming development efforts are ongoing using the ACC/DOE preforming machine at the National Composites Center in Dayton, Ohio to obtain an optimized preform.

Molding Development

Carbon-Fiber Plaque Molding

A series of preforms using Fortafil (now TohoTenax) fibers were molded. These contained different numbers of splits per roving and were molded over a range of fiber volumes. At a given fiber volume, there was only a small difference in the in-mold pressure between preforms of differing fiber splits. This was unlike the findings from the earlier Hexcel fiber study where the in-mold pressure increased with preforms of smaller fibers.

B-Pillar Molding

There were no full-scale molding trials for molding optimization during this period. The B-pillar molding during first part of the year was to support the evaluation of preforms produced on the Gen-2 screens. It was determined that while some of the preforming problems were solved with the new screens, there were other issues with the new design. Therefore, it was decided to complete the B-pillar development work using the original screens.

After an interruption for the carbon-fiber plaque work and maintenance on the press and preformer, B-pillar molding development has resumed. At this point the preform for the inner panel is nearly optimized and improvements to the outer preform are underway. A critical area of the outer preform has been identified where too much fiber will prevent the mold from fully closing (Figure 4). Heavy fiber loading in other areas of the preform did not have this same detrimental effect.

During the maintenance period, the control system for the French Oil press at NCC was reprogrammed to give a more linear press closing profile. The press closing rate was essentially uncontrolled and varied depending on the resistance to closing. This is demonstrated in Figure 5, which shows the separation between the upper and lower mold halves during the compression stage. The old closing profile was a variable rate event, while the modified closing has a nearly linear position vs. time profile. The improved closing profile will make the press a better tool for the continuing molding trials.

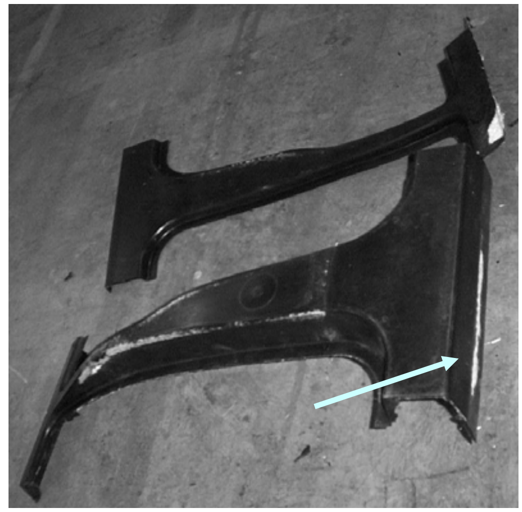


Figure 4. Arrow shows dry glass area in B-pillar where heavy fiber loading holds mold open.

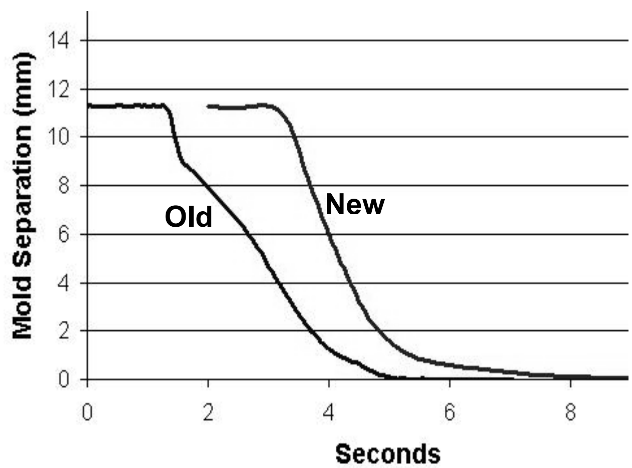


Figure 5. Comparison of old and new, more linear, closing profiles for the NCC press.

Flow Modeling

Prof. Suresh Advani of U. Delaware was contracted to develop a flow model for the molding of carbon-fiber preforms by the injection-compression process used in FP3. The intention was to develop and confirm a flow model with the B-pillar and then extend it to the full body side. This would be used as a design tool to assist in optimizing the location of the injection locations for body side molding.

The flow model has been completed for the B-pillar for both glass and carbon preforms. The predicted filling profile is very close to the observations made with short shots. The body side flow model has been completed for a single injection point, with the full, multiple-injection model to follow.

The mold filling of the full body side was modeled in a similar fashion to the B-pillar. The mold was assumed to be partially open with a gap between the preform and the upper mold half, with the resin injected into this gap (the injection step). This resin is initially pooled on top of the preform as shown in Figure 6 for an actual B-pillar molding. In the compression step, advancing resin front was modeled as the closing mold forced the resin through the preform. In this simulation the resin is considered to first be pooled in the gap between the preform and the mold, next the resin is forced into the preform, and finally the resin is forced throughout the preform, filling the mold. Figure 7 shows the model prediction at a point partway through the compression stroke, where the mold has contacted the preform, but not yet compressed it. At this point, the preform under the original resin pool is fully saturated, but the adjoining areas are only partially filled, and the flow has not yet reached the extreme ends of the mold. This model will be used to determine where additional mix heads need to be located to completely fill a complex part such as the body side.

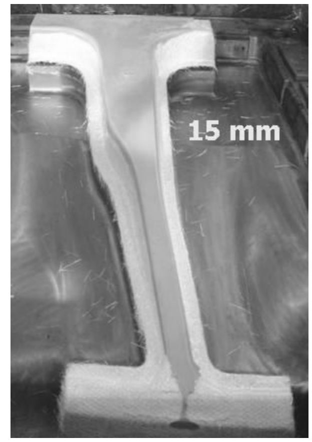


Figure 6. Resin pooled on top of B-pillar preform.

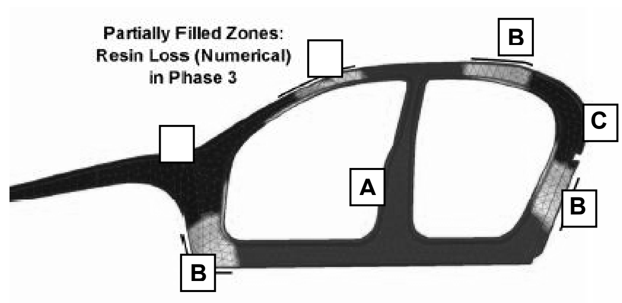


Figure 7. Flow model simulation of partially filled preform. (A) Completely filled preform, (B) partially filled cells, (C) empty preform.

B-Pillar Testing

A combined structural testing and structural modeling effort was established to evaluate the quality of the B-pillar. The B-pillar had not initially been modeled as an independent structure separate from the entire body structure. The structural testing program was therefore set up to define test cases to be modeled, and then provide experimental data to verify the structural model. This model would also predict the response of the structure to local fiber content variations, and also predict the difference between glass and carbon reinforcement.

The approach was to categorize potential defect type, location and magnitude, and then to determine which of the potential tests (loading conditions) would highlight the effects of these defects, and determine which tests are most sensitive to defects. A limited set of physical tests would then be down-selected, and the tests conducted. The tested bonded parts would be available for further analysis to evaluate any damage occurring during the test loading.

The 3-point bending and torsion loading cases were selected for the testing and cases to be modeled. The testing was performed at Defiance Testing & Engineering located in Troy, Michigan. Test fixtures were designed and built for these cases, and testing completed for the glass B-Pillar inners, outers and bonded assemblies. Figure 8 shows a B-pillar outer clamped into the 3-point bend fixture and ready for test.

A total of four B-Pillar inners, four bonded assemblies and four outers were tested in 3-point bend and torsion. It should be noted that the maximum load/torque was determined by loading the first sample of each test near its limits. Audible cracking of the inner panel was detected at 3.6 kN and for the bonded assembly at 2.4 kN. Therefore,

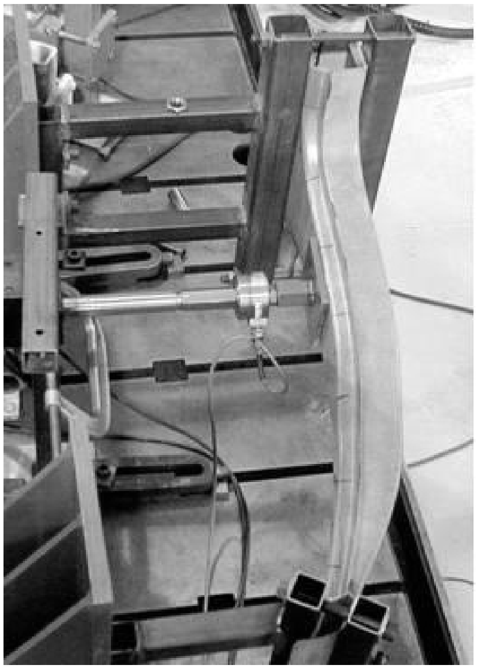


Figure 8. Bonded B-pillar in 3-point bend test fixture.

test loads for the additional parts were limited to 1.8 kN. An example of 3-point bend force-deflection curves for the inner, outer, and bonded assembly is shown in Figure 9. Results from the B-Pillar evaluation testing were used in the ACC FP3 modeling effort to evaluate the models used to predict component stiffness, with those results discussed below. The testing of the glass-reinforced B-pillars was judged to be very satisfactory, and the same procedure will be applied to the carbon B-pillars.

B-Pillar Structural Analysis

For the B-Pillar torsion and bending test cases, finite element analysis (FEA) was carried out using commercial FE code LS-DYNA. The objective was to identify the potential problems in structural analysis and to study the effect of fiber volume fraction on torsion and bending responses.

Variation in thickness and fiber volume fraction of the B-Pillar presents a challenge for FE modeling. The variation in thickness can be modeled via the use of solid elements. However, shell elements are preferred for full vehicle analysis. To develop a FE modeling strategy pertinent to full vehicle analysis, FE model was constructed with shell elements.

Thickness variation was digitized at 0.5 mm interval. Each shell element was assigned a thickness. As an example, Figure 10 presents assigned thickness variation for B-Pillar inner panel.

Two methods were examined to represent the material variation: (1) assume a nominal constant fiber volume fraction (volume %) and (2) divide the B-pillar into different zones based on its approximate fiber volume % and use a stress-strain curve according to its volume %. The material was assumed to be isotropic and modeled with a piecewise linear plasticity model (MAT24).

Torsion and bending simulations were carried out for inner, outer and bonded B-pillar. Torsion simulations were in good agreement with the experimental results in deformed shapes (Figure 11) as well as in responses (Figure 12). For bending cases, simulations predicted a much stiffer response. The FE model was modified with different boundary

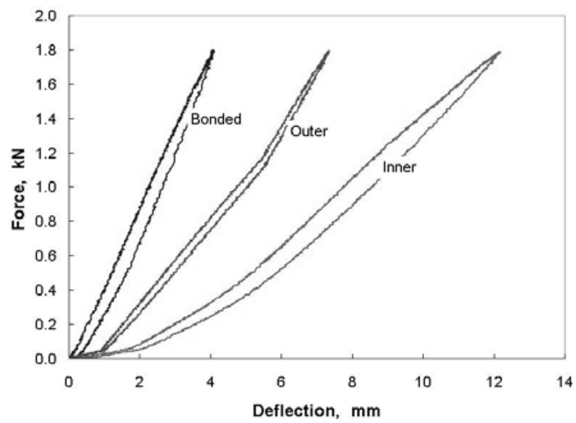
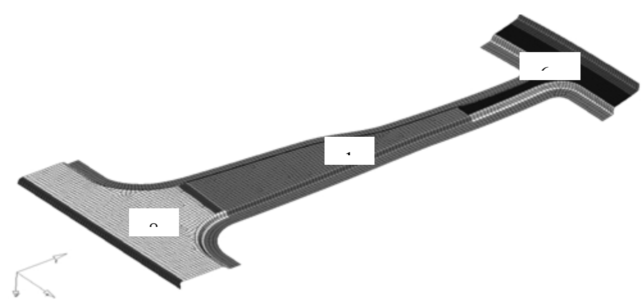


Figure 9. Example of force vs. deflection curves for the bonded B-pillar and the separate inner and outer panels.



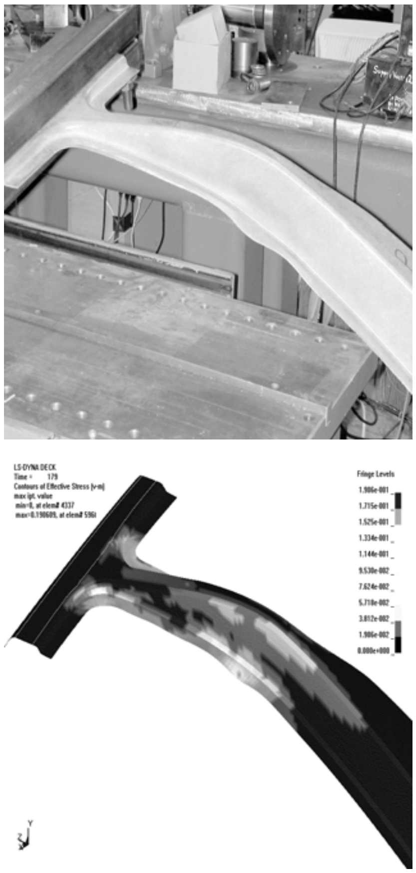


Figure 11. Deformed B-pillar outer in torsion test and simulation.

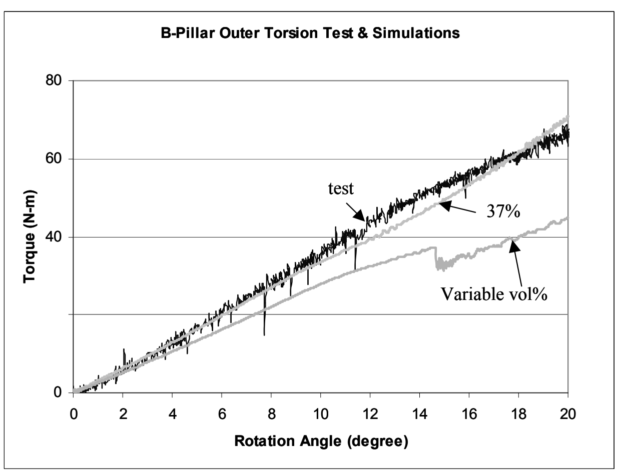


Figure 12. Comparison of simulations with experimental results for B-pillar outer torsion.

conditions and the results indicated that the resin nuggets left on the B-pillar surface prevented the piece being properly clamped in bending test. It is recommended that resin nuggets need to be removed in future tests.

Simulations results indicated that while the FE models with variable fiber volume % gave better correlations, the results of the models with a nominal constant fiber volume % were also acceptable. For the load cases analyzed, when compared to those with variable fiber volume %, the stiffness ratios were in the range of 1.1-1.2 and 0.866-0.95 for simulations with a constant fiber volume % of 37% and 30%, respectively.

The adhesive bond was modeled via tied nodes between the shell elements and the method appeared to be efficient. The width of the bondline was found to have a significant effect on the response (Figure 13). Examination of the hand applied bond line showed it to average less than the bond flange width of 25 mm. Using a bond width of 16 mm in the model gave good agreement with the experimental results.

Summary

Complete optimization of the B-pillar preform has turned out to be more difficult than originally envisioned. With the limited amount of suitable

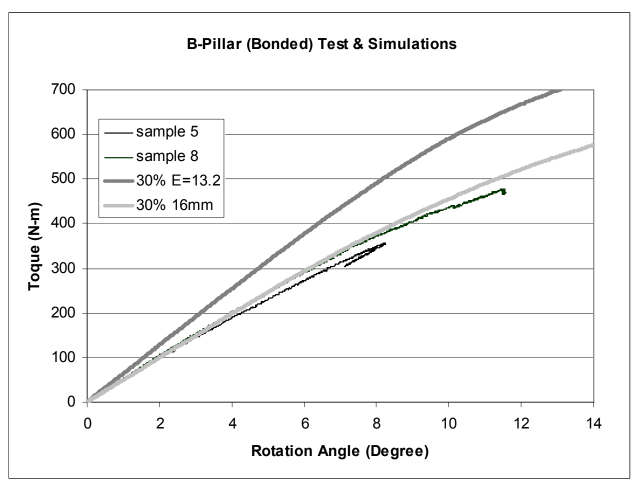


Figure 13. Comparison of experimental results with simulations with 25 mm and 16 mm bond width.

carbon fiber for preforming, it is necessary to optimize the preform with glass prior to the carbon-fiber molding.

The preform optimization is nearing completion and carbon-fiber molding will start in the near future. Most of the remaining items needed for completing the project are in place: the bonder has been tested, the structural testing demonstrated, and the structural model developed.

External Publications

Stanley Iobst, Jeff Dahl, Libby Berger, Jessica Schroeder, Dan Houston, and Mike Mao, "Automotive Composites Consortium B-Pillar Molding Program," Presented at Society of Plastics Engineers Automotive Division, September 12-14, 2005, Troy, MI, and published in the Conference Proceedings.

ACC Technical Reports

Stanley Iobst, "Automotive Composites Consortium Carbon Fiber-SRIM Plaque Molding," May 2005.