AUTOMOTIVE COMPOSITES CONSORTIUM
B-PILLAR MOLDING PROGRAM

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Abstract

The Automotive Composites Consortium is conducting a program to develop a design and manufacturing strategy for a composite intensive body-in-white (BIW). This BIW is to have 60% mass savings compared to a corresponding steel structure, meet all structural requirements, and be manufactured at 100,000 units per year at cost parity to current processes. A key element of this design was to use a liquid molded, chopped carbon fiber reinforced composite with a fiber volume fraction of 40% for the body side component of this structure. This process has the advantages of producing variable section thickness to optimize the structure at minimum mass, while each element in the process has been demonstrated to have a 4 minute cycle. Preforming and molding tools representing the B-pillar portion of the body-side design were designed and built. These were used to investigate the processing of high fiber content chopped fiber composite in the shape of the main contours of the body-side. The first phase of this program was to develop the basic preforming and molding with glass fiber roving. Once this is accomplished, the program will move to carbon fiber. This paper reports the development of preforming, molding, bonding, and testing in the initial phase of the B-pillar program.

Introduction

The Automotive Composites Consortium (ACC) Focal Project 3 (FP3) program is intended to develop and demonstrate the use of carbon fiber composite structures to generate significant weight savings for an automobile body-in-white (BIW). The first phase of the program was a structural design study, previously reported by Johnson and Boeman [1]. This study determined that a carbon fiber intensive body-in-white could be produced with a 60% mass reduction over a corresponding steel structure. A part breakdown of 23 composite panels was proposed. One outcome of this study was to use a variable wall thickness on some of these panels to maximize the structural efficiency at minimum mass. Among the goals of the program was to demonstrate the cost-effective manufacturing technology for the BIW at a production rate of 100,000 units per year. This directed the design towards the use of single laminate bonded panels rather than cored structures.

The body-side structure was selected by the FP3 team to be the demonstration project for this program. It would highlight many of the necessary key elements for this program, including the automated processing of low-cost carbon fiber and variable thickness wall sections. In addition, this was one of the most challenging parts of the FP3 design. The shape of this part made it very cost inefficient to use fabric reinforcement, while the sprayed chopped fiber reinforcement would be a very efficient use of fiber, and build on an existing ACC competency.

To manufacture a cost efficient structure, the FP3 team proposed using low cost carbon fiber roving to be preformed by the Programmable Powdered Preforming Process (P4) [2] and molded by structural reaction injection molding (SRIM) [3]. Both the molding and preforming technologies were demonstrated earlier in the ACC FP2 program, but with glass fiber at lower volume fractions. That program used a glass fiber reinforced composite pickup truck box, with 30% fiber loading at 3 mm panel thickness, as the demonstration part [4]. The FP3 structural design showed that a 40% volume loading of carbon fiber and a minimum panel thickness of 1.5 mm were required to meet mass targets. Producing the highly reinforced panels required for this program is considered to be a processing stretch. The processing path of liquid molding of chopped fiber preform was selected as being necessary to meet production rate targets. Each stage of this process was demonstrated in FP2 to have a cycle time of 4 minutes.

The B-Pillar Molding Program was planned as the process development step to bridge the gap between plaque molding and the full FP3 body-side molding program. The part selected to be tooled was the B-pillar portion of the body-side, roughly 1100 mm tall with about 450 mm of the upper and lower rail sections, shown in Figure 1. It consists of two panels, an inner and an outer, which are bonded together to form the structure. It will be used to generate data on the preforming and molding characteristics of high volume fraction carbon fiber preforms of complex shape, and assist in the final design of the body side tooling. B-pillar inners and outers will also be produced for bonding and structural analysis studies. This program is under the direction of the ACC FP3 team with major funding from the Department of Energy (DOE).

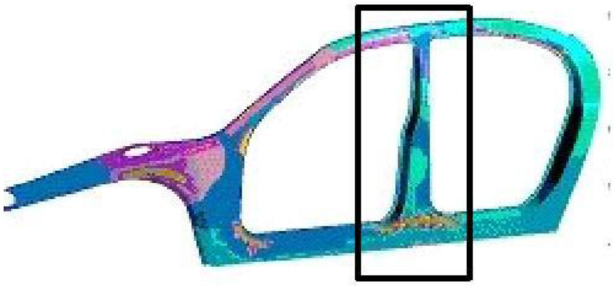

Figure 1. Body side design showing the portion selected for the B-pillar program. Colors represent design thickness ranging from 1.5 mm (pale blue) to 8 mm (orange).

B-Pillar Design

Selecting the B-pillar for the development part incorporated most of the geometric features of the full body-side design. However, while the body-side was designed with continuously changing wall thickness to minimize the structure weight, the B-pillar was simplified to three areas of constant wall thickness in each panel.

Figure 2 shows the drawing of the outer panel of the B-pillar design with the areas of different thickness. The main vertical area was 1.5 mm thick, the minimum wall thickness of the body-side design. The lower rails were 6 mm for the outer and 8 mm for the inner panel. The upper rails were 4 mm for the outer and 6 mm for the inner. Thus the full range of thickness from the body-side design was incorporated into the B-pillar design. The mold also had the bonding flanges so that the inner and outer panels could be assembled into the completed B-pillar. The bonding flanges were all 2 mm thick. The walls had a constant taper from the face thickness to the bonding flange. The section depth of the outer panel was about 90 mm and the inner 30 mm.

Since the B-pillar was intended to be primarily a learning tool for preforming, molding and bonding, it was simply sectioned from the body-side design, and did not have specific independent structural requirements. It also was not intended to be joined to any existing automobile sections. While structural tests were conducted on the B-pillar, the testing criteria were based on experience with similar body structures.

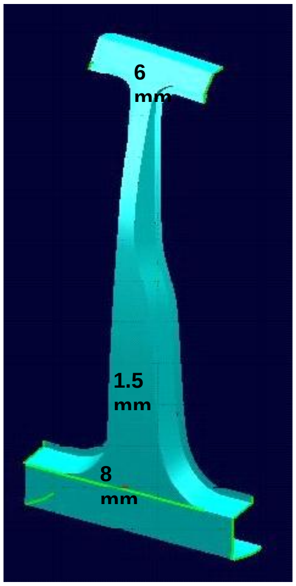

Figure 2. *B-pillar outer panel.*

Preform Tooling

Although hammer formed steel preform screens are typically thought to be dimensionally inferior to composite preform tools, steel screens offer several advantages relative to composite tooling. Steel preform screens provide superior heat resistance during the preform heating/cure cycle. In the same way, the inherent heat resistance allows them to be PTFE coated to enhance preform release and de-molding. Additionally, the need to perforate the tool is eliminated as pre-perforated steel screens are utilized. Finally, steel screens provide superior durability relative to composite preform tools.

Based upon these factors, it was determined that the B-pillar preform tooling be manufactured using pre-perforated steel sheet via a hammer forming process. To enhance preform release and de-molding characteristics, the completed preform screens were coated using a reinforced polytetrafluoroethylene (PTFE) material. The completed B-pillar inner and outer preforming tools are shown in Figure 3.

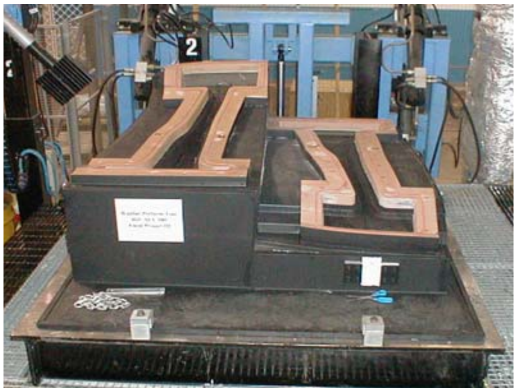

Figure 3. B-pillar preforming tool

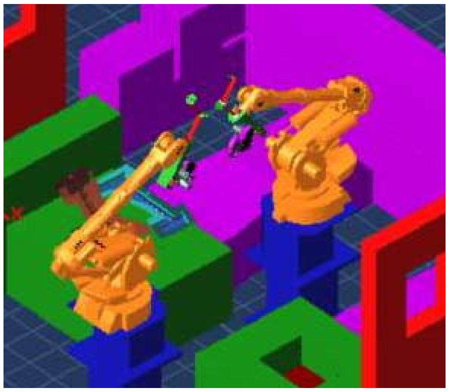

Figure 4. e-M workplace model

In order to enhance B-pillar preform tooling design and reduce preform lead times, e-M Workplace offline programming software was used to develop a model for the ACC's preforming equipment (Figure 4). The e-M Workplace model, along with the B-pillar inner/outer and tooling runoff surface data, was then used to develop robot targets (i.e., positions) and robotic paths for the Focal Project 3 B-pillar inner and outer preforms. Upon completion of robotic paths, the location of both the B-pillar inner and outer preform screens on the press platen (x, y, z) were optimized within the constraints of the machine by examining robot reach and collisions (robot to tooling, robot to chopper gun, chopper gun to tooling) in an iterative process. The data generated was used for the final design and build of the B-pillar preforming tool. Additionally, the robotic paths generated offline were downloaded to the actual robots for execution and subsequent manufacture of preforms.

SRIM Tooling

The B-pillar mold was built to be versatile for use with multiple processes such as SRIM, thermoplastic compression molding, and SMC (sheet molding compound). It was constructed with P20 steel and has a polished surface so that it can be used to develop class-A surface techniques later, if desired. Both the inner and outer cavities were placed into the same mold, but the cavities were not connected and each cavity had a dedicated mix head. The mix heads were mounted in the upper mold half and recessed into the tool so that the exit of the mix chamber was at the cavity surface and no sprue was required. The parts were located with the outer surface facing up, so that the preform was placed on the core in the lower tool half. A schematic drawing of the orientation of cavities in the mold is shown in Figure 5.

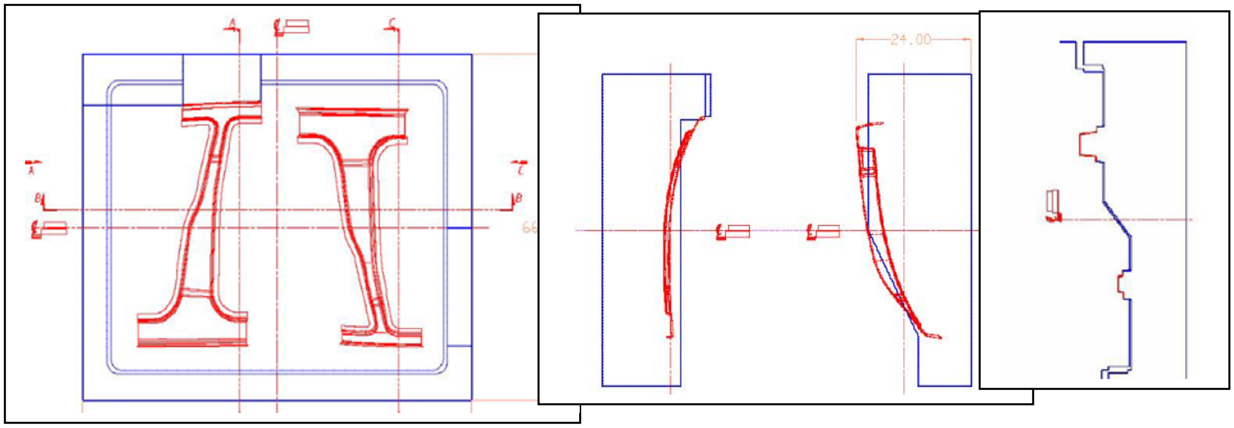

Figure 5. Drawing of the orientation of the B-pillar inner and outer panels in the mold.

The B-pillar is highly curved, and in order to accommodate the tool draw, a large elevation change in the cavity surface was required. The mix head ports were located at the position of equal resin volume to each end of the mold. This gave equal flow, but different flow lengths to each end of the mold cavity. Also, at those locations, the far end was downhill for the outer cavity, but uphill for the inner cavity. The mold was fitted with an external vacuum shroud that was engaged when the separation of the two mold halves was less than 100 mm. This allowed the cavities to be evacuated before the resin was injected.

Internal resin seals were incorporated to contain the resin within each cavity. Three pressure transducers were installed in each cavity, one near the injection point, and one at each end of the cavity. The mold had linear displacement transducers (LDT) at each corner, so that the mold closing dynamics could be recorded. Figure 6 shows the mold installed at the molding location, the National Composite Center (NCC), Kettering, OH [5].

Figure 6. Photograph of molding cell, with upper mold half booked, at NCC.

Preforming

Preforming process development has been ongoing to facilitate manufacture of the B-Pillar inner and outer test sections. Due to the variable thickness design of the B-pillar inner and outer (1.5-8.0 mm), the preforms require a wide range of fiber densities to achieve the target fiber volume fraction of 40% in each thickness zone. Due to both cost and the limited availability of a suitable carbon fiber material, the majority of preform development to date has been conducted using glass fiber.

Offline developed robotic programs using e-M Workplace were successfully implemented allowing fabrication of prototype preforms on the same day the tooling was commissioned. It is estimated that by utilizing ROBCAD, preform lead-time was reduced by four weeks versus teach mode programming. Although utilization of offline programming tools expedited the robotic programming process allowing preform manufacture, the resultant preforms were only prototypes and not of sufficient quality for SRIM molding.

In order to enhance preform quality, substantial robotic programming was required to achieve the appropriate fiber volume fraction in regions of the components that vary from 1.5 to 8.0 mm in thickness. Despite these programming efforts, localized material distribution issues remain on both B-pillar inner and outer preforms when manufacturing preforms at a fiber volume fraction of 40%. Material distribution issues are predominantly evident in 1.5 mm regions (Figure 7) of the components and in the 1.5 mm sections of thickness transition areas of 4, 6, or 8 mm to 1.5 mm. 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. This is exacerbated depending upon the thickness requirement and part geometry for a region in close proximity to the 1.5 mm regions. The variation in component thicknesses, 1.5, 3.0, 4.0, 6.0 and 8.0 mm, correspond to glass fiber areal densities of 1536, 3072, 4096, 6144 and 8192 g/m^2 respectively.

Figure 7. Areal density distribution issues in a molded B-pillar outer, 1.5 mm section, glass fiber preform

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. Large areal density variability within the preform due to these issues has led to subsequent molding issues including fiber wash and dry regions in the parts.

Process development on the B-Pillar inner and outer is an ongoing effort in support of the ACC's Focal Project 3. Progress has been made in improving the material distribution and will continue to be an iterative effort between preforming and molding. Several preforming related technical hurdles have been identified that can be attributed to part geometry coupled with variable part thickness, the most challenging of these being the 1.5 mm regions adjacent to thicker sections. Based upon the preforming development performed to date, the results suggest that a 1.5 mm part thickness at a fiber volume fraction of 40% is extremely challenging and may be at or beyond the current process capability. A reduction in fiber volume fraction may be required for consistent preforming and to achieve high quality components in the 1.5 mm regions. However, the remaining thicknesses (3.0, 4.0, 6.0 and 8.0 mm) appear technically feasible in the preforming process at a fiber volume fraction of 40%.

Molding

While the B-pillar is much smaller than the entire body-side, incorporating both cavities into the same tool gives a molding size roughly equivalent to a door surround. All molding was done using glass performs at a fiber volume of 40% by the injection/compression. In this technique, the perform is loaded into the mold, and then the mold is closed to the injection gap, a few millimeters above stops. At this point the vacuum is engaged, the resin is injected and the mold fully closed, i.e., the compression stage, to force the resin throughout the mold cavity. The Baydur 420IMR resin was injected into the 75°C mold at a rate of 450 g/s and a ratio of 1.23 polyol to 1.0 isocyanate. The mold was opened two minutes after injection. The typical preform weighed 1.3 kg and 2.3 kg after molding. Mold filling was characterized by a number of techniques including a series of short shots, data traces, and observation of any patterns of dry fiber areas. The series of successively larger short shots shown in Figure 8 demonstrate how the resin fills the mold.

Figure 8. Flow characterization by short shot experiments, showing the resin fill pattern with progressive fills of 25%, 50%, and 75%.

The data acquisition system allowed the resin injection and press closing dynamics to be observed. An example data chart is given in Figure 9, which shows the mold initially paused at a gap of 3.7 mm above stops for injection. Following injection, the mold was fully closed, forcing the resin through the preform and pressurizing the cavity.

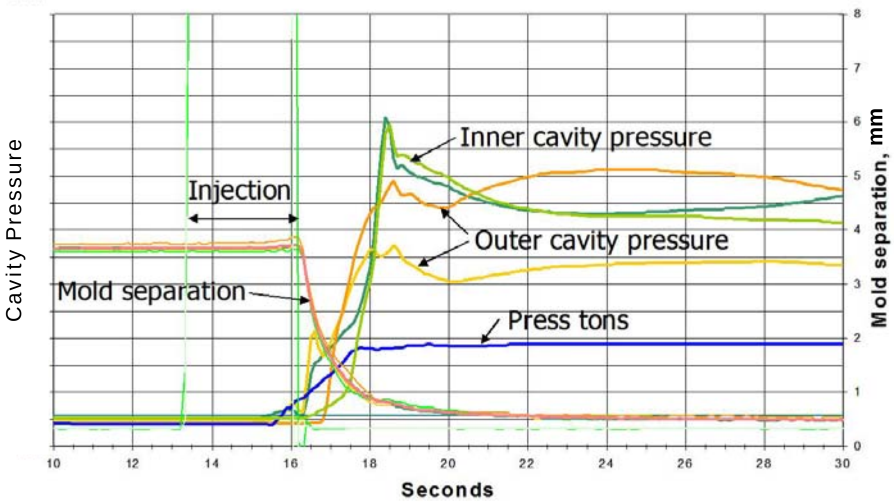

Figure 9. Data chart for SRIM injection/compression molded B-pillar.

Experimental factors in the initial molding study included the injection gap height, the time between injection and compression, and the press tonnage. The injection gap height was found to be an important parameter due, in part, to the significant curvature of the B-pillar. In order to accommodate the mold draw, this curvature caused a large vertical separation between the ends of the cavities. Also, the part is designed with a thin section between the two thicker ends, which prevents any excess of resin in one end from flowing back towards the other end of the part. With too large of an injection gap, too much resin flowed towards the lower part of the cavity and the opposite end of the part did not fill. If the injection gap was too small, the flow resistance was too great and the mix-head over pressurized and faulted out. However, by controlling the injection gap to between 3 and 7 mm, a good initial resin distribution was obtained, giving completely filled parts as shown in Figure 10.

Figure 10.   Molded B-pillars in the lower mold half.

The initial molding phase was completed, establishing molding parameters, supplying feedback to preforming, and producing parts for testing.

Material Property Testing

A representative B-Pillar was sectioned for tensile and fiber volume testing according to the templates shown in Figure 11. The tensile samples were cut and tested as straight-sided, 25 mm wide samples according to the ACC test manual [6].

The results are shown in Figure 12 as tensile strength and modulus plotted against glass fiber volume fraction. Glass content was targeted as 40 volume%, but actually averaged 33.3 volume% for the outer panel (range 16.2 to 48.7) and 33.5 volume% for the inner (range 20.8 to 46.6). The ranges correspond to coefficient of variation values of 26% for the outer and 28% for the inner. The tensile modulus values are compared to the values predicted by the Halpin-Tsai equation [7] for various contents of random chopped fibers. Up to about 40 volume%, the tensile modulus values for the outer panel follow the prediction fairly well. Point OT-12, however, is significantly above the prediction. This sample is taken from the bottom end of the outer panel, just below the curve. This is an area of not only high fiber volume 48.7 %, but also a place where fibers could easily align in the direction of the tensile bar. This alignment would give higher mechanical properties than would be predicted for random fibers. The tensile modulus values for the inner are almost all above the Halpin-Tsai prediction, indicating that most of these samples have significant fiber alignment.

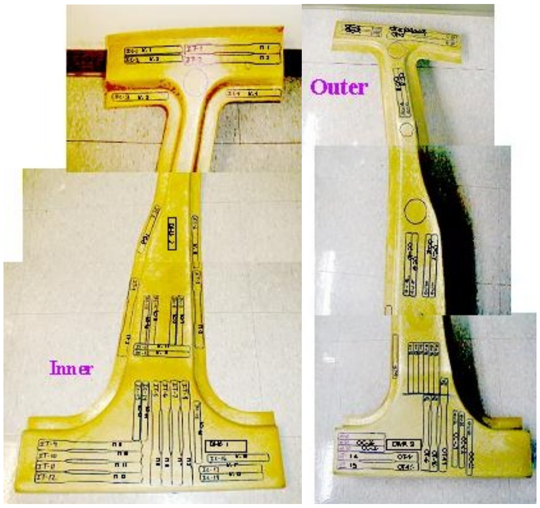

Figure 11. Location of test samples for material property testing of B-pillar.

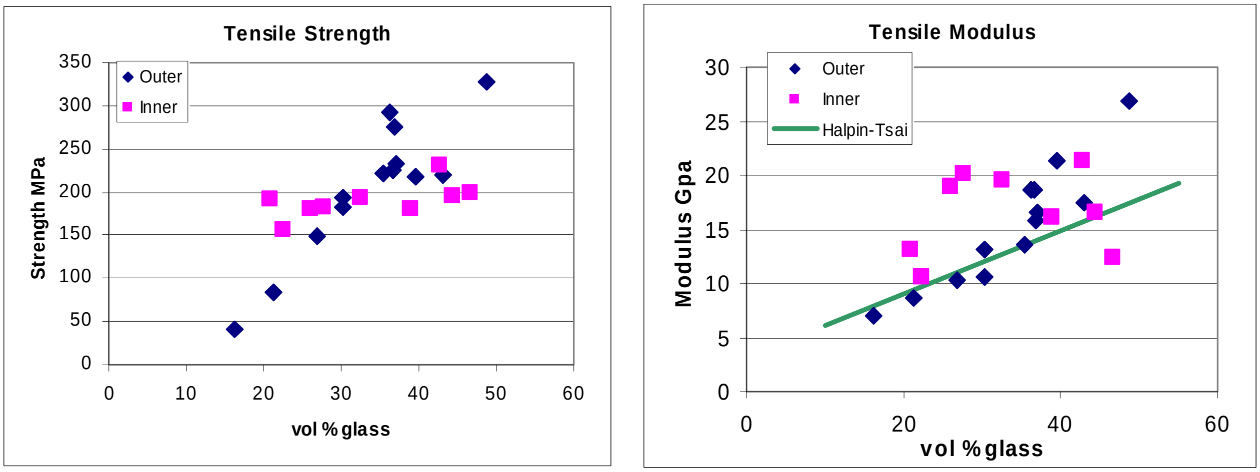

Figure 12. Correlation of tensile strength and modulus as a function of glass content. Modulus is compared to the predicted value from the Halpin-Tsai equation.

The tensile strength trend with glass content is similar to the modulus trend. The values for the outer panel are fairly linear, with point OT-12 again being the highest value. The inner panel strengths show less variation with glass content. Again, this is likely due to a high degree of glass fiber alignment in the samples, which predominates over the actual glass content.

Bonding

The 2-piece molded "learning" B-pillar was also intended to allow the team to demonstrate assembly capability. To that end, the Joining Work Group focused on the use of structural adhesive bonding as a key enabling technology for the assembly of large composite parts. Initially, as in the current work, B-pillars were fabricated from glass-reinforced composite.

The adhesive chosen to bond the B-pillars was a 2-part version (re-formulated and optimized by the supplier for production) of the 1-part adhesive used to bond the ACC composite pick-up truck box, SIA (now Henkel) EXP654 ETG [4]. The new adhesive was designated Sovereign Specialty Chemicals SIA 731 SI, a 2-part epoxy which cures in 2 minutes at 127°C. This adhesive was formulated by the supplier to accommodate a reasonable amount of wax-based mold release so that only minimal surface preparation was required for bonding. To confirm the choice of adhesive prior to attempting to bond the B-pillars, lap shear tests were performed using material sectioned from a B-pillar as the substrate. Results from the lap shear testing are given in Table I and Figure 13. Lap shear strengths ranged from approximately 7 MPa to 12 MPa. These strengths, along with the observed fiber tear failure mode, indicated that bonding the B-pillar substrate with the 2-part SIA epoxy gives acceptable results. Fiber tear indicates that the bond interface is stronger than the substrate being bonded and is a preferred failure mode for bonded composites.

Table I: Lap Shear Strengths of B-Pillar Substrate Bonded with SIA 731SI Adhesive

Substrate Thickness (mm)	Lap Shear Strength (MPa) (replicates)	Failure Mode
1.7	7.4 ± 0.6 (3)	Fiber tear
2.0	6.8 ± 0.8 (4)	Fiber tear
6.1	11.9 (1)	Fiber tear

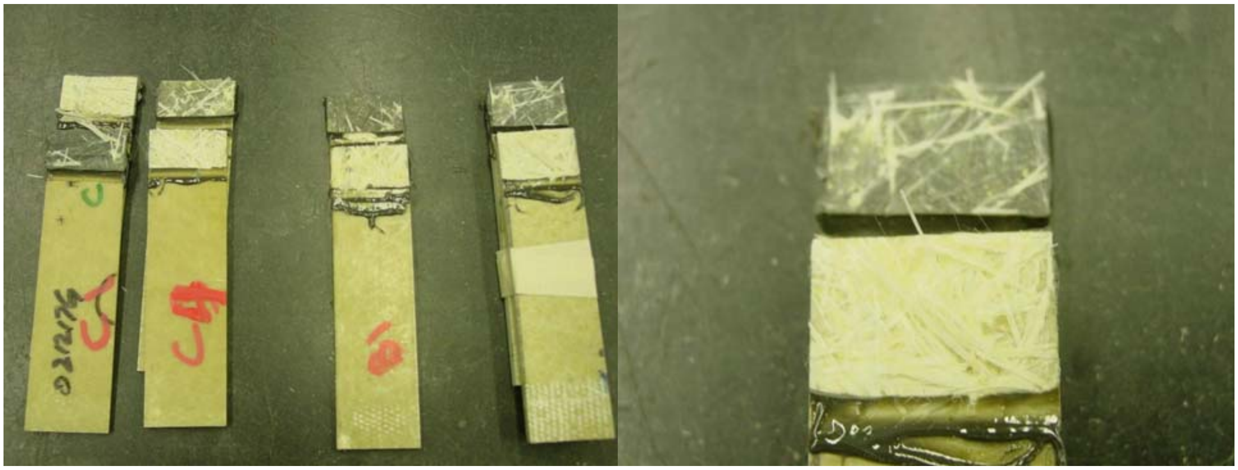

Figure 13. Examples of fiber tear failure of lap shear samples (B-pillar substrate bonded with SIA 731 adhesive).

The B-pillar bonding fixture consisted of a base with a cavity to hold the B-pillar outer and clamps to hold the inner in place on top of, and mated to, the outer. The shape and dimensions of the cavity were obtained from the CAD data used to build the mold for the B-pillar sections along with a “splash” from the actual mold. The bond fixture was designed with only a single cavity to allow for any dimensional variability of the experimental parts. The cavity was held in place on a base-plate and surrounded by an air duct which fed hot air to channels around the part cavity and out through orifices spaced every 2 cm. These orifices opened just under where the bonding flange of the B-pillar outer rested when it was in the cavity. The air was supplied though a manifold at approximately 10 kPa, and the total cure cycle - the air temperature, the cure time and the cool-down time - was programmed via a digital controller. Thermocouples were placed in the hot air line and the bond line to monitor both the inlet air temperature and the actual adhesive temperature during cure. The fixture and controllers are shown in Figures 14 and 15 along with an example of the B-pillar inner and outer panels prior to bonding.

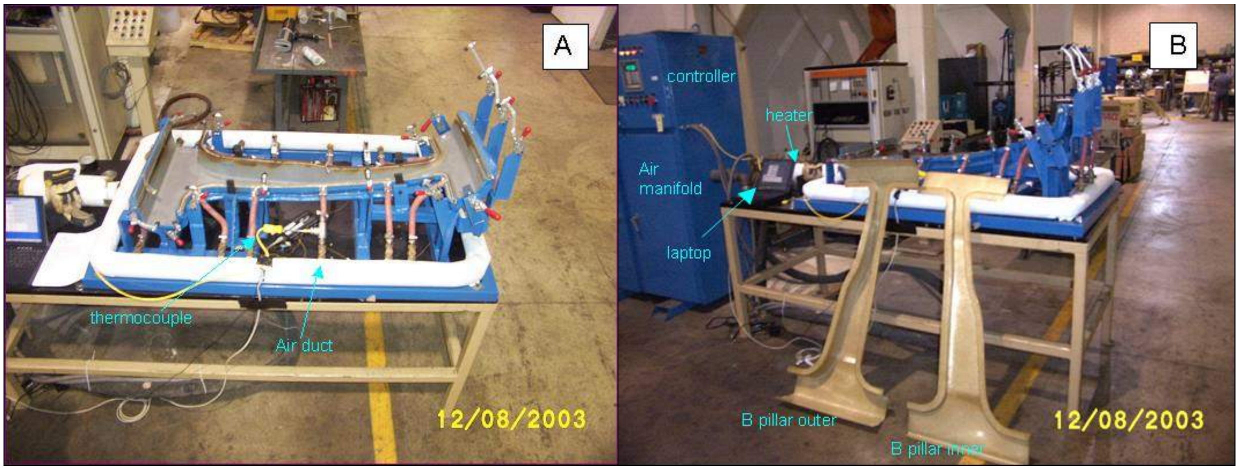

Figure 14. A) B-pillar bond fixture with cavity for outer and hot air duct (white) and B) Bond fixture showing controller and manifold (blue), heater and B-pillar sections: outer (left) and inner (right).

The B-pillar inners had been molded with “stand-offs” spaced every 5 cm to control the bond thickness to approximately 0.76 mm. The adhesive bead was applied manually, using an air-assisted dispensing gun, on the entire perimeter of the B-pillar outer. The outer, with adhesive, was placed into the bond nest cavity, the inner was then manually placed on top of the outer sitting in the nest, making certain that the two sections were aligned. Finally, all the clamps were closed and excess adhesive wiped off. After several iterations, a successful adhesive cure cycle was determined to be holding the bond line 110°C for 600 seconds.

Of the bonded assemblies produced, two were assessed for dimensional correctness using a coordinate measuring machine (CMM). The CMM checking was used to determine whether the bonded B-pillar assembly was within tolerance; 32 bond and 23 surface locations were used as the programmed check points for evaluating dimensional correctness. The tolerance programmed for the CMM check was ± 1 mm, which was deemed reasonable for a prototype part [8]. Since the composite B-pillar is envisioned to be molded, ultimately, as part of an entire body side, it would not need many of the attachments required for a conventional (steel) side structure (e.g., meeting weld and/or rivet mating locations at roof and rocker rail and maintaining clearances at these locations). However, there will still be requirements for meeting and/or locating the latch plate and door hinge attachment. In any case, to meet the

Figure 15. Part with inner placed on top of outer in bonding position; clamps in closed position

programmed tolerance requires that both the composite thickness and shape are as-designed, and that the bond thickness is correct. For both of the assemblies evaluated, for the total of 128 bond and 92 surface coordinate measurements (x, y, z, t) for each part, about 9% of the bonds and 27% of the surfaces were out of programmed tolerance. The surface numbers exhibit a higher percentage "out of tolerance" because they are a combination of bond and composite thickness measurements, each with their own errors. For an initial trial of a non-optimized part, however, these results are encouraging. Therefore, the bonding trial was deemed to have been successful.

Structure Testing

A whole panel structural test was defined for the B-pillar. This testing will aid in assessing the quality of the as-molded B-pillar inners, outers and bonded assemblies to provide feedback for performing and molding process development. Two load cases, 3-point bend and torsion, were defined for this testing. The bonded assemblies and the individual molded B-pillar inner and outer panels were used to evaluate these tests

Deflection Test Set Up

The 3-point bend test stand fixed the sample at both ends. Pinch clamps were used on the top and bottom of the pillars. When clamping the bonded samples, two spacers were inserted into the bottom of the pillar to fill the void. The clamps at each end were welded to test fixtures that mounted to a bedplate via angle stands. The test samples were loaded with a 150 mm by 150 mm square plate in a direction orthogonal to the B-Pillar surface. A hydraulic actuator was used to generate the load (measured by a load cell) and displacement was measured using an LDT in the actuator. Figure 16A shows a B-pillar outer clamped into the 3-point bend fixture and ready for test.

The torsion test was performed on an existing test stand. It utilizes a rotary actuator to supply torque and a torque cell to measure it. The samples were run using angular displacement control with feedback from an angular displacement transducer (RVDT). The samples were clamped and oriented such that the bottom of the pillars were level and parallel to the face of the torque cell. The top ends of the pillars were fixed to a bedplate via the clamping fixture. The torsion input was aligned with the center of the B-pillar bottoms. Figure 16B shows a B-pillar outer clamped into the torsion fixture and ready for test.

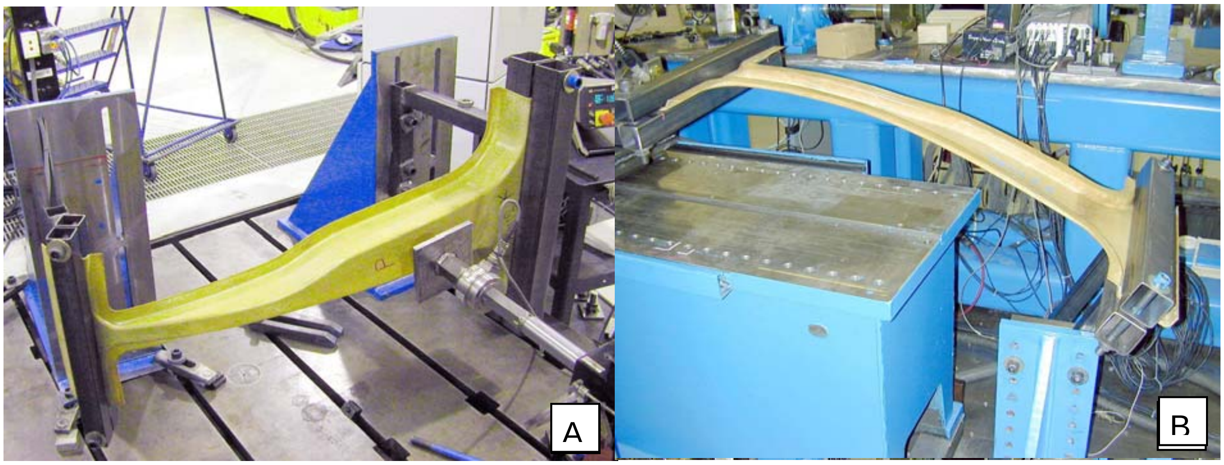

Figure 16. B-pillar test setup: A. Outer panel in 3-point bend. B. Inner panel in torsion.

Test Results

A total of four B-Pillar inners, four bonded assemblies and four outers were tested. Data was colleted using a Labview data acquisition system and was provided in ASCII format. The maximum load/torque was determined by loading the first sample of each test near its limits. Audible cracking of the inner panel was heard at 3.6 kN and for the bonded assembly at 2.4 kN. Therefore 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 17. Results from the B-Pillar evaluation testing will be used to evaluate the models used to predict component stiffness.

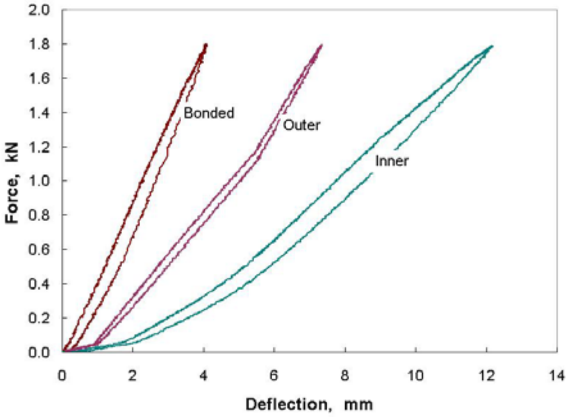

Figure 17. Example force vs. deflection curves for the bonded B-pillar and the separate inner and outer panels.

Summary

A B-pillar shaped portion of a composite automobile body structure design is the test bed for a complete composite body-in-white. In this initial phase of the program, the preforming and molding this complex structure has been demonstrated with glass fiber. The two component panels were been bonded together into the completed B-pillar structure, which was measured to be within acceptable tolerances. This is a partial demonstration of the feasibility of the Automotive Composites Consortium's Focal Project 3, which is to demonstrate the feasibility of manufacturing a carbon fiber intensive automobile body-in-white exhibiting a 60% mass savings compared to a corresponding steel structure.

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