## Development of a Cost Competitive, Composite Intensive, Body-in-White

**Raymond G. Boeman** Oak Ridge National Laboratory

### Nancy L. Johnson

General Motors Corporation

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#### ABSTRACT

The Automotive Composites Consortium has initiated the third of a series of focal projects, which is a multiyear program to develop a design and manufacturing strategy for a composite intensive body-in-white (BIW) with aggressive mass reduction, manufacturing cycle time, and cost parity targets. Specifically, the BIW is to exhibit 60% minimum mass savings over the conventional steel baseline, contain the same package space as the baseline, meet or exceed the structural performance, and have cost parity to the baseline in volumes exceeding 100,000 per annum. The Department of Energy's Office of Advanced Automotive Technology provided most of the funding for this project. A design study was undertaken to evaluate whether the mass savings are feasible - utilizing carbon-fiber composites - without sacrificing structural performance. The design was conducted with consideration to costeffective composites manufacturing processes that are under development. This paper will present objectives of this focused program, results of the design study, and a discussion of the technical challenges that will be addressed during the remainder of the program.

#### INTRODUCTION

Successful deployment of highly fuel-efficient vehicles relies on the development of technologies that result in significant mass reduction. To that end, the U.S. Department of Energy Office of Transportation Technologies (DOE/OAAT) and the United States Council for Automotive Research (USCAR) are undertaking research programs to develop advanced materials, manufacturing processes, and assembly techniques for automotive structures. One of the central areas of this research is the development of polymermatrix composite technology for structural applications. This has been the focus of the Automotive Composites Consortium (ACC), one of the consortia under USCAR, since its inception in the late 1980's. Recent success with glass-reinforced polymers has demonstrated that structural components can realize mass reductions of up

to 30% compared to traditional steel structures. This is generally considered the upper limit of mass savings attainable with glass fiber composites. Other materials are required to reach beyond 30% mass savings. One of the most promising candidate materials is carbon-fiber composites, which have the potential to reduce automotive component weight by 60%. Consequently, DOE/OAAT has established as a goal of its Lightweight Materials (LWM) Program, the advancement of carbonfiber composites technology to realize maximum mass savings potential, and to do so cost-effectively.

As a key element of the composites research within the DOE LWM Program, the ACC is undertaking a demonstration project which will serve as a focal point of the automotive industry/DOE collaborative research in materials, manufacturing processes, assembly, and crash energy management. The ACC is a research and development partnership of DaimlerChrysler, Ford and General Motors. Working with key suppliers, the first phase of the third focal project – to design and analyze a composite-intensive body-in-white structure – was completed.

#### OBJECTIVE

A composite-intensive body-in-white (BIW) was selected as the focus for the collaborative research efforts. The ACC undertakes focal projects to coordinate and direct cross-functional research activities by producing automotive structures that demonstrate generic processing, assembly materials. design, and developments. The composite-intensive BIW project will assist in establishing stretch goals and provide focus for research activities within the ACC/DOE collaborative composites research program. The requisite research will be conducted by the FP3 team, ACC working groups, DOE direct-funded projects, and key suppliers.

FOCAL PROJECT GOALS - The specific goals of the focal project are to design, analyze and build a composite-intensive BIW that demonstrates:

- Manufacturing processes to enable production volumes exceeding 100,000 per annum
- Minimum 60% mass savings with respect to a steel baseline BIW
- Equivalent package space as the baseline
- Equivalent or greater static bending and torsional stiffness performance as the baseline
- Satisfactory durability performance
- Manufacturablity at a comparable price to the baseline

A complete dynamic crashworthiness analysis on the BIW was not considered to be within the scope of this project since the requisite tools for predicting the crashworthiness of composite structures are not yet available. The Energy Management Working Group of the ACC is working on the predictive code development. Currently, to accomplish such an endeavor would require extensive empirical data on both components and full vehicles. This approach would be expensive. Consequently, the design was undertaken with consideration of front crash and roof-crush only to estimate the additional material mass required for structural integrity of the passenger cell structure. It is emphasized here that design of a full-crashworthy BIW is not an objective of this effort.

<u>BIW Baseline: DaimlerChrysler JA</u> – The Daimler-Chrysler JA platform (Dodge Status, Plymouth Breeze, Chrysler Cirrus circa 1995-2000) served as the baseline for mass, performance, and cost comparisons. The baseline vehicle is shown in Figure 1. Mass and performance baselines and targets are given in Table 1.



**Figure 1.** DailmerChrysler JA platform was selected as a baseline for mass and performance comparisons.

Table 1. N	Mass and performance crit	eria for a composite-
	intensive body-in-w	hite.

Criteria	Baseline (Chysler JA)	Composite- Intensive BIW
Mass	262 kg	105 kg
Static Bending Stiffness	5.2 kN/mm	≥ 5.2 kN/mm
Static Torsion Stiffness	8.5 kNm/deg	$\ge$ 8.5 kNm/deg

<u>BIW Focal Project Phases</u> – The composite-intensive BIW focal project is comprised of three phases. The first phase, which is the subject of this paper, consists of: a) generating conceptual designs; b) selection of the BIW concept through finite-element analysis and structural optimization using stiffness constraints; c) refinement of the body structure with more detailed finite-element analysis, and structural optimization for all load cases; d) determination of technology development needs; and e) initiation of the requisite materials and process research.

The second phase, outside the scope of this paper, will principally focus on the development and refinement of materials and processes for high-volume production techniques. This will be accomplished by focusing on one or more components that represent the most challenging barriers and opportunities presented by large-scale use of carbon-fiber composite structures in high-volume, low mass applications. For the selected components tooling will be designed and built, assembly fixtures fabricated, and prototype components will be manufactured with the same materials and processes proposed in Phase I, that is, for high-volume, costcompetitive manufacturing. Limited component testing will be undertaken as appropriate to verify performance characteristics.

In the final phase, the remaining tooling and components of the BIW will be manufactured. This will be done principally with non-production tooling and processes due to funding restrictions. The BIW will be assembled and verification testing will be completed.

# PRELIMINARY DESIGN AND ANALYSIS OF THE BODY-IN-WHITE (BIW)

Considerable time and effort was extended in the initial task of Phase I – generating novel BIW concepts. Every attempt was made to incorporate the advantages of composites such as parts consolidation and integration. Although no materials or processes were established a *priori*, it was generally recognized from inception that to achieve the mass target the BIW would have to utilize carbon fiber composites at a significant level, and that foam or other cores should be used sparingly, if possible. Cost considerations also guided the conceptual phase in terms of limiting the use of

expensive, high-performance, aerospace-grade composite and core materials, although selective use was not forbidden. The working assumption was that the BIW would be manufactured with random chopped carbon fiber composites to the extent structural performance would permit. Low-cost processes such as the P4 preforming process [1, 2] for random chopped carbon fiber composites are currently under development within the ACC.

CONCEPTUALIZATION OF THE BODY-IN-WHITE – Roy Bonnett, a consultant with considerable experience in composite BIW design, was engaged to develop multiple BIW concepts. Through deliberations with the project team, which was comprised of automotive industry experts in materials, processing, joining, and crash energy management, the concepts evolved into the conceptual design depicted in Figure 2.



Figure 2. Paper concept of the composite intensive body-in-white.

In developing the concept, deliberation was given to viable processes and materials, parts consolidation opportunities, joint configurations to reduce peel stresses, single-station assembly, and assembly sequence, as well as overall weight and cost considerations. Individual part size was not restricted. Part complexity was limited to what was believed to be viable with existing or emerging high volume composites processes. The processes being considered included liquid molding, compression molding, thermoplastic stamping, and extrusion/pultrusion.

Features of the concept included minimum number of parts, body-side inner/outer pair bonded together, multiple cross-car structures, and energy management rails integrated into the body-sides. Additionally, the use of cores was minimized to save mass.

CONCEPT DEVELOPMENT – To further refine the BIW, Engenuity, Ltd of Cuckfield, UK was engaged to conduct finite element analyses and optimizations for a range of novel concepts derived from the concept depicted in Figure 2. CAD data for the JA baseline structure was obtained and used as the basis for the analysis and design studies.

<u>Design Concepts</u> – The following concepts were developed and analyzed:

- Concept 0: Existing JA BIW design with composite properties substitution
- Concept 1: Similar to paper concept design (Figure 2)
- Concept 2: Similar to Concept 1 with increased sections and without B-pillar
- Concept 3: Similar to Concept 1 without rocker inner
- Concept 4: Similar to Concept 1 with enlarged rockers and pillars

In the interest of computational efficiency, the modeling at this stage was restricted to global geometry with minimal detail. For example, detail of joints (e.g., bond flanges) and features less than 10 mm were excluded. Each concept was subjected to analysis and optimization to assess its relative merit in satisfying the project goals. The optimization procedure is described below.

<u>Stage 1 Optimization</u> – Optimization was done with the objective to minimize mass while satisfying only stiffness targets. In this stage, the optimized designs were not required to satisfy other load cases such as durability. Composite properties in this stage were restricted to random-oriented, chopped carbon-fiber composites. These results provided an efficient basis to evaluate the relative merits of each concept. Detailed analyses were done later on a selected concept, as will be discussed in a later section.

Prior to optimization, the thickness was assigned a constant value, 10 mm, for the entire structure. Altair Optistrut Topography optimization routines were then used to move material from less highly stressed areas to more highly stressed areas. The optimization process was done iteratively until convergence was met. The results from the Optistrut stage were a grouping of elements of equal thickness, which served as the initial condition for the next stage. Up to this point the derived thickness values were relative, not absolute. Altair Hyperopt was then used, with MSC Nastran as a solver, to optimize the thickness of each grouping to their Maximum and minimum thickness absolute value. constraints were set according to anticipated processing limitations and were 10 mm and 1.5 mm, respectively.

Optimization results from the second optimization stage are presented in Table 2. All concepts converged to meet the mass targets when constrained to satisfy the bending and torsional stiffness requirements. Total mass and stiffness efficiency were used as figures of merit for comparison of the various concepts. It is important to recall that the results in Table 2 are for simplified geometries that lack detail of attachment (e.g., no bonding flanges, inserts, etc.) and without features smaller than 10 mm (e.g., holes, fillets, etc.). Consequently, the BIW mass for each concept, as presented in Table 2, is considerably lower than ultimately required for the fully optimized BIW. Those results will be presented later in this discussion for a single concept. Never the less, the results indicate that the mass targets appear reasonable.

Concept	Mass (kg)	Bending Efficiency (Stiffness/kg)	Torsion Efficiency (Stiffness/kg)
Concept 0	102	52	84
Concept 1	62	85	241
Concept 2	62	84	222
Concept 3	74	70	184
Concept 4	58	89	260

Table 2.	Resultant mass and stiffness efficiencies for	
	concepts without geometric detail.	

The most promising concepts were Concept 1 and Concept 4 based on a combination of mass reduction and stiffness efficiency. The lower mass and higher stiffness efficiency of Concept 4 as compared to Concept 1 was attributed to the large sections in the rocker and pillars. However, these larger sections significantly reduced the passenger entry/egress. Consequently, Concept 1 was selected, over Concept 4, for further development. The optimization result for Concept 1 is illustrated in Figure 3. The color denotes the thickness groups ranging from 1.5 mm to 10 mm. Note that the majority of the structure is at minimum thickness (1.5 mm).

#### DETAILED DESIGN AND ANALYSIS OF BODY-IN-WHITE (BIW)

A detailed design and analysis were conducted on Concept 1. The process was similar to that outlined above but with three major distinctions. First, all load cases including stiffness, modal, durability, abuse and crash, were considered in the analysis. Second, the model included detailed features such as bond flanges, inserts, adhesive, and suspension loads and mounts. Third, woven carbon fiber composites were considered for sections that were essentially rectangular and consequently would have minimal material scrap.



**Figure 3.** Thickness groups for the model of Concept 1. Thickness groups range from 1.5 mm to 10 mm. The model used to generate these results ignored joining details such as bonding flanges and features less than 10mm.

Strictly speaking, automated optimization was done only for the stiffness conditions. The resulting structure was then analyzed for all load cases. Where the structure was found to be deficient for any load case, the design was modified by, in general, adding material thickness. The analysis was then rerun for each load case followed by subsequent design modifications until performance requirements were satisfied for all load cases simultaneously. Figure 4 illustrates this iterative procedure.



**Figure 4.** Iterative process for optimization of the body-in-white with respect to several load cases.

FINAL DESIGN AND PART BREAK-UP – The final design of the structure is shown in Figure 5. It consists of twenty-three components.



**Figure 5.** Final design of the composite intensive body-in-white. Each color denotes a separate component.

Significant modifications from the preliminary design include separating the lower rail sections, wheel arches, and quarter panels from the body-side in favor of individual components for each. Random chopped carbon-fiber composites were selected for the majority of the panels. Stitched or woven fabrics with cores were selected for the reasonably flat, regularly shaped floor and roof panels. Braided tubes were envisioned for the lower rails.

For mass prediction, aluminum inserts were included for:

- Door mounts
- Engine mounts
- Seat floor mounts
- Strut tower
- Wishbone mount
- Seat belt
- Rear suspension bracket

ANALYSIS RESULTS – Linear static finite element analyses were undertaken using MSC Nastran V70.7. Static design load cases included: stiffness, abuse (door loads), seatback pull, roof crush and modal analysis. Two load cases included inertial effects and represent dynamic test conditions: durability loads and front crash. Equivalent static loads reacted by the inertia of the structure were used to analyze durability load cases using inertial relief techniques within Nastran. Inertial relief techniques were also used for front crush analysis.

<u>Stiffness</u> – As the initial optimization developed, it was apparent that, due to the efficiency of the BIW structure, the torsional stiffness target of 8.5 kNm/deg was readily satisfied and the over-riding constraint was the bending stiffness target of 5.2 kN/mm. The addition of extra materials and inserts to meet other performance targets resulted in both stiffness targets being exceeded – bending by 12% and torsion by 103%.

<u>Durability</u> – The peak stresses within each component were compared against the maximum allowable stress

for each load case analyzed. Knockdown factors were applied to the static strength for each load case based on estimated lifetime cycles. Knockdown factors were based on the durability research conducted at the Oak Ridge National Laboratory in collaboration with the ACC Materials Working Group [3]. The maximum allowable stress was not exceeded in any load case. The worst load case was rear pothole braking, which was within 15% of the allowable.

The peak stresses in the aluminum inserts, adhesive, woven carbon fabric, and core were, in general well below allowable levels. This was then conservatively compared to the allowable stress level for the highest cycle event. The peak stresses in the aluminum inserts occurred in the strut top and were only 60% of the allowable stress, which indicates the possibility of further weight reduction through either insert optimization or integration into the strut tower part.

The maximum allowable stress at the highest cyclic loading for woven carbon fabric was only 40 % of target. This would normally indicate the possibility of additional weight reduction by reducing the thickness further. However, further thickness reduction might compromise the damage tolerance of the structure to transverse impacts such as encountered during stone kick-ups.

Polyurethane foam properties were used for the analysis of the sandwich structure core. The maximum shear stress in the core was 60% of the allowable. In general the axial and shear stresses in the adhesive were significantly below allowable levels. In some instances individual bond elements adjacent to inserts were highly loaded and exceeded allowable stress levels for the highest cyclic loading. However this analysis was undertaken to assess the bulk loads in the adhesive, rather than detailed adhesive stresses.

<u>Abuse Loads</u> – Initial results indicated that the door over-opening load case gave rise to significantly higher stresses than other abuse load cases. Therefore, the initial development of the structure concentrated on the door over-opening load case. Verification took place using the door sag load cases after development. The final analysis showed that the maximum peak stress in the chopped carbon near the check strap area on the Bpillar was below allowable. The maximum peak stress in the aluminum inserts that reinforce the hinges was well within the allowable level. The displacements seen at the latch for all load cases were comparable with a similar size steel vehicle.

<u>Modal Analysis</u> – The frequency of global modes can be used for comparative analyses with similar size vehicles and are an indication of how the vehicle will respond to dynamic loadings. As the BIW exceeds the stiffness targets (significantly for torsion), and is approximately 40% the mass, it is not unexpected that the modal results are approximately double their targets at 60.5 Hz and 63.4Hz. for torsion and bending respectively. <u>Seat Belt Pull Results</u> – The stress results from the seat belt pull analysis were all predicted to fall within allowable levels. The most highly stressed regions were in the woven fabric areas of the floor around the tunnel and seat belt inserts. The B pillar was shown to perform adequately under the applied loads. The analysis indicated some high stress regions on the underside of the sill behind the B-pillar however these could be attributed to the local restraints applied in this region.

Results Although demonstrating Crash \_ crashworthiness is not an objective of this project, front crush and roof crush were investigated using inertial relief techniques to estimate the additional material mass required for a crashworthy passenger cell structure. The full dynamic effects of the impact are not completely addressed with this approach but by employing knockdown factors of 33% for material strength, reasonable estimates for the robustness of the backup structure are assumed. Front crash performance of the structure was developed with respect to two key criteria: controllable crush of the rails, and stability and integrity of the passenger compartment. For the latter, the intention was to conduct a frontal impact load analysis to determine the stresses within the passenger cell structure for comparison to static allowable values.

*Front Crash:* The results indicate that stresses within the passenger cell structure did not exceed the allowable stress, which was one-third of the static strength for the material. The stability of the front rails was also demonstrated to the extent that stress levels in the rails behind the crash force application points were less than half the static strength, and were also evenly distributed around the section. The stress levels in the adhesive elements showed that the bonds between panel flanges were generally subjected to low loads. Detailed stress analysis of the stresses in the seatbelt inserts under crash loads was undertaken separately. Engine mounts are assumed to detach from their supports during a front crash event in this design.

*Roof Crush:* A static roof crush analysis showed that all stress levels within the composite layers of the sandwich structure were kept below allowable levels. The stress levels in the core layer of the sandwich structure, close to the load application point, indicated that local crushing of the core may be expected under roof crush conditions.

<u>Part Thickness</u> – The dramatic weight savings of this design is due in part to the optimization of part thickness within a component. This is most notable for the body-side inner and outer. Thickness contour plots were generated for each part of the body-in-white. Figures 6 and 7 show the thickness range for the outer and inner body sides. The assumed material is a 40% by volume, random chopped carbon composite.



Figure 6. Idealized thickness variation for body-side inner from twostage optimization process.

The thickness variations are dramatic and change rapidly. It is currently unknown how rapidly thickness can be changed for each of the processes under consideration; therefore these variations represent a bound on the mass savings.

<u>Total BIW Mass</u> – The total mass of the BIW structure was predicted to be 86.2 kg. The actual body-in-white mass will be slightly higher due to manufacturing constraints – yet unknown – on the thickness variations. However, it is expected that 60% mass reduction will be attainable. Key structural inserts considered during this phase of the analysis, some of which have been analyzed in detail, weigh 6.4 kg. An additional insert mass of 2.4 kg was included as an estimation of what the numerous other, less structural, inserts might weigh.



Figure 7. Idealized thickness variation for body-side outer from twostage optimization process.

#### FUTURE WORK – MATERIALS AND PROCESSING DEVELOPMENT NEEDS

Based on the design and analysis results of Phase I of the focal project, further materials and processing developments necessary for the demonstration part (Phase II of the project) have been identified. Key manufacturing requirements include:

- Minimum thickness of 1.5 mm in large complex parts
- Fiber volume fraction of at least 40% for random chopped carbon composites
- Low variability in material properties within a part
- Significant variations in section thickness within a part – 1.5 mm to 8 mm with low material scrap rates
- Short molding cycle times to achieve desired production rates

Cost modeling efforts are also underway to quantify the cost-efficiency of the design, which is based on low-scrap, highly automated processes as well as low-cost carbon fibers. These technology developments are being undertaken within the ACC/DOE collaborative research program, as well.

#### CONCLUSION

A composite intensive body-in-white has been designed and optimized that exhibits a mass reduction of greater than 60% with respect to the steel baseline BIW while satisfying stiffness targets. Predictions of bending and torsional vehicle stiffness exceed values for the baseline vehicle. Durability, abuse, and modal criteria were satisfied as well. Crash performance, based on a static analysis for frontal crash and roof crush was used to estimate additional mass requirements to strengthen the passenger cell structure. Cost considerations were used to define potential materials and processes but cost modeling efforts are still underway and therefore cost competitiveness is still unknown. Significant stretch goals have been established to guide further carbonfiber composite materials and processes technology development efforts within the ACC/DOE collaborative research program.

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#### CONTACTS

Nancy Johnson is chairperson of the compositeintensive BIW project and is a lab group manager for vehicle crashworthiness at General Motors Research and Development Center. She can be reached at 586-986-0468 or Nancy.L.Johnson@GM.COM.

Ray Boeman is an automotive composites specialist on assignment in Detroit, Michigan to work with the Focal Project team. He also works with the Materials, Processing, Joining, and Energy management Working Groups of the ACC to develop composites technology. He can be reached at 248-452-0336 or BoemanRG@ORNL.GOV.