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Structural Optimization of Automotive Body Components Based on Parametric Solid Modeling

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Abstract. *Parametric modeling was used to build several models of an automotive front structure concept that utilizes carbon fiber composite materials and the corresponding molding processes. An ultra-lightweight aluminum body front structure was redesigned to include an all-composite front structure. Two alternative concepts were studied which represent the structure as a bonded assembly of shells. Closed sections result from two pieces – an inner and outer. Parametric modeling was found to be a useful tool for building and modifying models to use in optimization concept studies. Such models can be built quickly and both the sketch dimensions and location dimensions are particularly useful for making the adjustments necessary to fit the various body pieces together. The parametric models then must be joined together as one geometric solid model in order to obtain a surface mesh. Structural optimization input data can then be seamlessly and quickly created from the parametric-model-based finite element model to begin the tradeoff studies. This integrated process in which parametric modeling was coupled with structural optimization was used to carry out design studies on the lightweight body front structure. Several carbon fiber material combinations were studied to determine mass reduction potential of certain types of carbon fiber products considered to be lower cost than typical carbon fiber materials used in the past. Structural optimization was used to compare several composite constructions for the design of the bonded front structure. Eight cases were studied using various materials and composite lay-ups. Mass savings estimates from 45–64% over steel were obtained. The most reasonable design consisted of a combination of relatively low cost chopped carbon fiber and woven carbon fiber and using a 20 mm balsa core in the top of the shock tower area. This design had a maximum thickness of 7 mm and a mass reduction over steel of approximately 62%.*

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1. Introduction

The structure shown in Fig. 1 is a lightweight body composed of several advanced materials. The design of this body was documented in Prsa [1] and was carried out as a part of the PNGV [2] government program. With the primary design goal being weight reduction, the PNGV body weighed approximately 70% less than the Chrysler Cirrus steel body it is intended to replace. The body is primarily composed of a sandwich construction of carbon fiber skins and aluminum honeycomb. Small amounts of Kevlar were also used as well as some Nomex core. However, the load-carrying members of the front structure are aluminum. This paper describes a project to redesign an all-carbon fiber front structure. Several concepts were considered. The concepts described in this paper can be characterized as bonded-together sheets that form closed-section rails. The concepts were modeled using the parametric modeling features of Unigraphics® (UG) [3], and are shown in the next sections. The mesh was created automatically using the Scenario capability of Unigraphics.

Fig. 1. Carbon fiber body.

Because the mesh was created based upon a solid geometric model, separate property regions were automatically created for each surface face. This made the optimization data creation phase much easier than previous studies [4]. Programs such as Patran® [5] can create optimization data automatically from properly created structural analysis data. This paper also describes the use of Nastran ® [5] Solution 200 to carry out design studies for composite design concepts for the front-end structure.

2. Parametric Modeling

The parametric modeling process begins with two-dimensional parametric cross-sections which are used to create solid models through extrusion along a straight line or sweeping along a curve. The front structure shown in Fig. 1 was modeled, using this parametric process, as bonded-together composite sheets. The model is composed, primarily, as three major components; the upper rail, lower rail, and shock tower. Other *secondary* panels tie these three components together. As an example, Fig. 2 shows the parametric cross section of the outer piece of the upper rail. The dimensions shown are variables that can be changed either by the designer using the modeling program or automatically using optimization procedures. After a variable is modified, the entire solid model is automatically updated. Figure 3 shows the process of creating three-dimensional geometry from the two-dimensional sections. As the section is swept along the curve, solid geometry is automatically generated. When any of the underlying information is modified, e.g., section dimensions, sweep curve location, etc., the solid geometry is automatically updated. Similar operations are used for the lower rail and the shock tower to obtain the complete parametric solid model that will be used in this design study, shown in Fig. 4. Figure 4 represents a three piece composite structure (upper rail, lower rail, and shock tower/apron) joined together with adhesive.

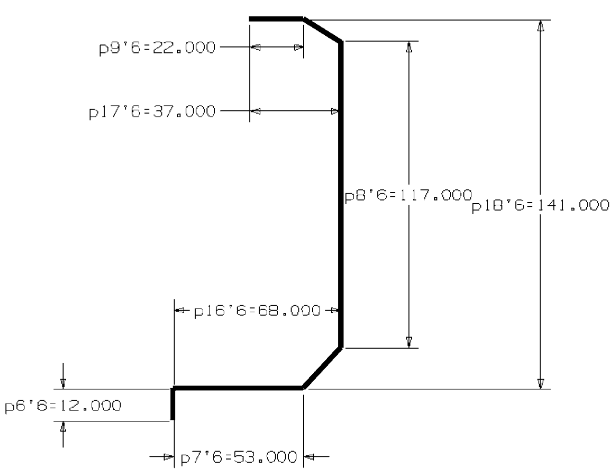

Fig. 2. Outer piece of upper rail.

For the purposes of this design study, parametric modeling was only used as a convenient method to create the finite element model. Ultimately, however, a more comprehensive design approach would allow the parametric model to be an integral part of optimization process where the parametric dimensions are available to be used as design variables. This is possible, to a large extent, with versions of Unigraphics 16 and later and has been demonstrated in Botkin [6].

3. Finite Element Analysis

3.1. Mesh Generation

The mesh shown in Fig. 5 was created from UG Scenario® using the fully-automatic quadrilateral mesh generation capability using a nominal 10 mm element size. This is an advancing front technique typical of those found in most commercial modeling programs. However, because of the tight integration between the parametric modeler and the mesher, the distinct surface regions shown in Fig. 4 are maintained as property regions in the mesh and, as shown in Fig. 6, can be automatically specified as design variables in the optimization model. The model shown in Fig. 5 is composed of 11,710 nodes, 12,225 elements, 58,877 degrees-of-freedom, and 23 different element properties. In addition to 11488 shell elements, 737 CBAR elements were used to represent adhesive bonds that were used to join the composite pieces together.

3.2. Analysis Model

Figure 5 also shows the load and boundary conditions used in this study. The goal of this optimization study is to design an all-composite front structure to have the same stiffness as the composite/aluminum structure shown in Fig. 1. The torsional stiffness of the structure in Fig. 1 was found to be [1] 10,246 N·m/deg. It was found by an analysis of the shock tower region that the stiffness is much higher than that of the overall body at 17,963 N/mm in the vertical direction and

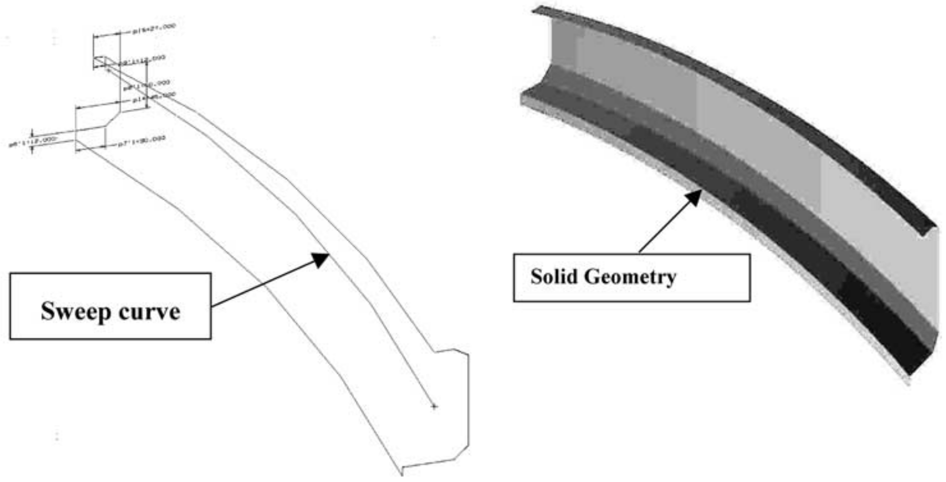

Fig. 3. Tapered upper rail.

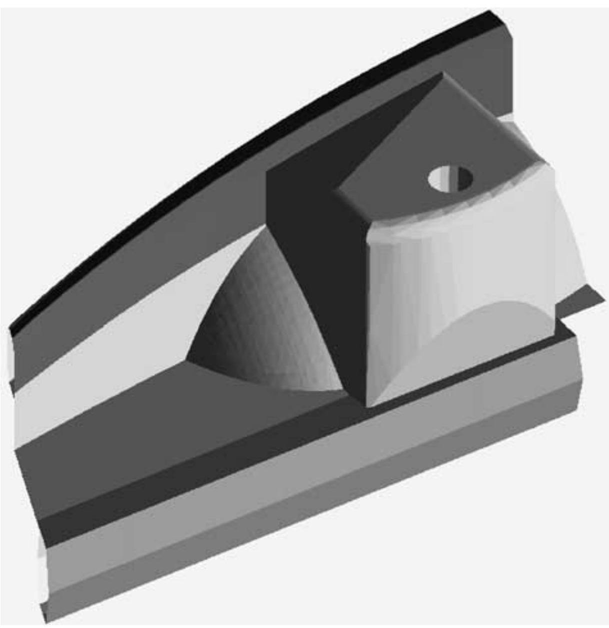

Fig. 4. Final front structure model.

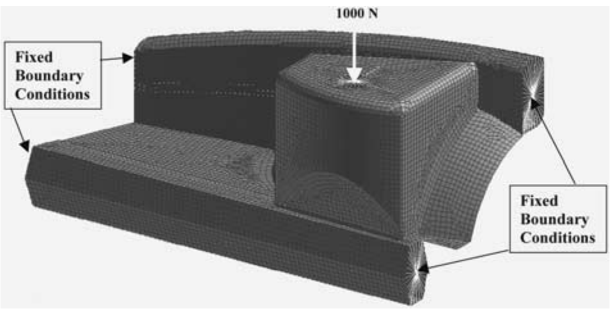

Fig. 5. Final mesh from UG/Scenario.

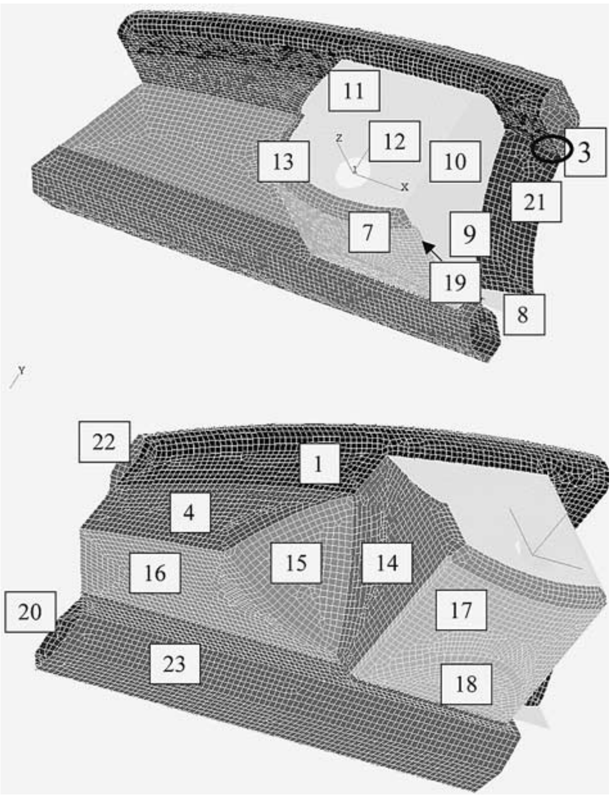

Fig. 6. Material property regions.

12,941 N/mm in the lateral direction. That corresponds to a limiting deflection of .055 mm for the 1000 N load shown in Fig. 5 and .077 mm for a similar lateral 1000 N load.

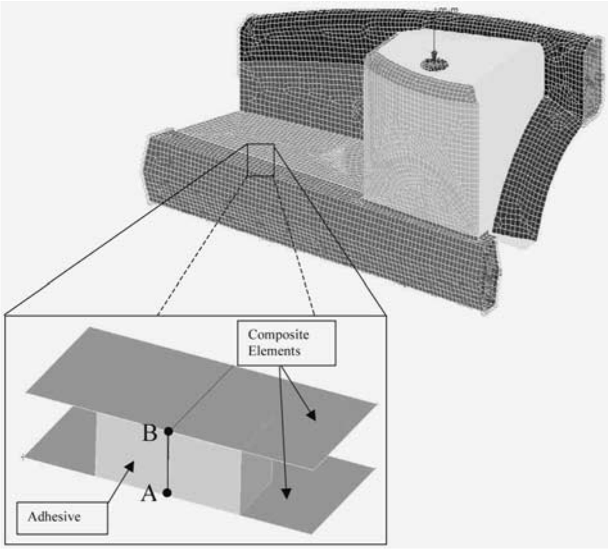

Fig. 7. Bond model.

3.3. Bond Modeling

As noted earlier, the three individual composite pieces are to be joined by the use of adhesives. Figure 7 shows the modeling approach chosen for this study. The rows of elements along the edges of each piece are joined by the use of beam elements for which the properties are determined from the material properties of the adhesive (shown in Table 1). The beam properties are the area of the bond considered to contribute to nodes A and B (see Fig. 7) and the moments of inertia. These values are 50 mm^2 and 416.67 mm^4, respectively, assuming a nominal element size of 10 mm (square).

4. Optimization Studies

Nastran Solution 200 was used to carry out eight case studies of various combinations of materials. The material properties are given in Table 1. All of the default Nastran optimization parameters [7] were used except the approximate optimization technique which was chosen to be Convex Linearization [8,9]. As noted in Botkin [4], *convex linearization*, which is the most conservative of the approximation methods available in Nastran, was used because of the difficulty of approximating the failure constraints.

4.1. Objective and Constraint Functions

The objective function of the studies was minimum mass. The design was, as mentioned earlier, for stiffness-only. Constraints were imposed on the lateral and vertical deflections of 0.077 and 0.055 mm, respectively.

4.2. Design Variables

As mentioned previously, the design variables can automatically be created from the property regions shown in Fig. 6. Figure 8 shows the panel from Patran [5] which is displayed when the Design Study tool is used. Although there are 23 design variables, not all are shown on a single panel. Initial values can be modified using this panel and then the Solution 200 data input (DESVAR & DVPREL1 card images) is automatically created. It should be

Table 1. Composite properties [4]

E_1 (Mpa)	E_2 (Mpa)	μ	G (Mpa)	ρ (kg/mm^3)	X_t (Mpa)	X_c (Mpa)	Y_t (Mpa)	Y_c (Mpa)	S (Mpa)
Chopped Carbon Fiber 26000	26000	.34	9701	1.36E-6	178	143	178	143	50
Carbon Plain Weave 52000	52000	.06	4200	1.43E-6	530	370	530	370	75
Uni-directional Material 130000	9000.	.3	4800.	1.50E-6	1630.	840.	34.	110.	60.
HYSOL EA 9395 Adhesive 4937.	4937.	.34	1842.		55.	96.	55.	96.	27.
Baltek D-100 balsa wood core 4070.	4070.	–	159	1.5E-7	13.1	12.9	13.1	12.9	3.0
Baltek D-57 balsa wood core 2240.	2240.	–	108.	1.0E-7	6.9	6.5	6.9	6.5	1.8

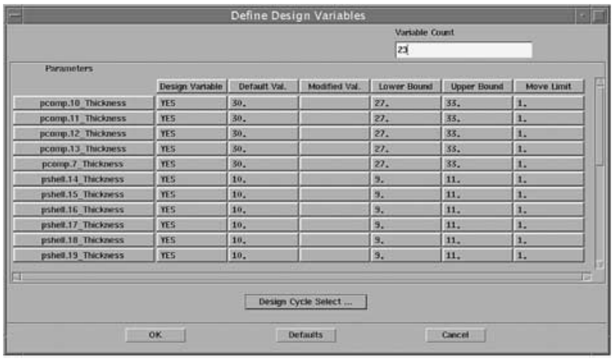

Fig. 8. Design variable panel.

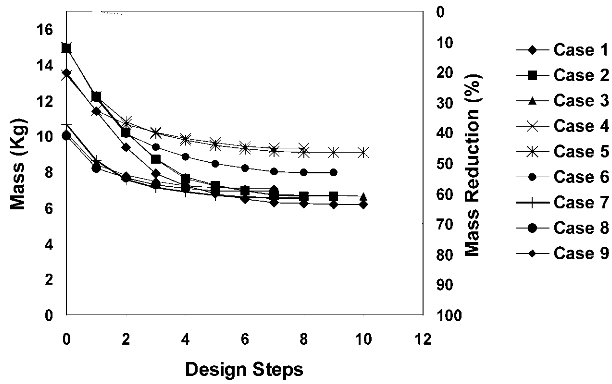

Fig. 9. Mass summary of cases.

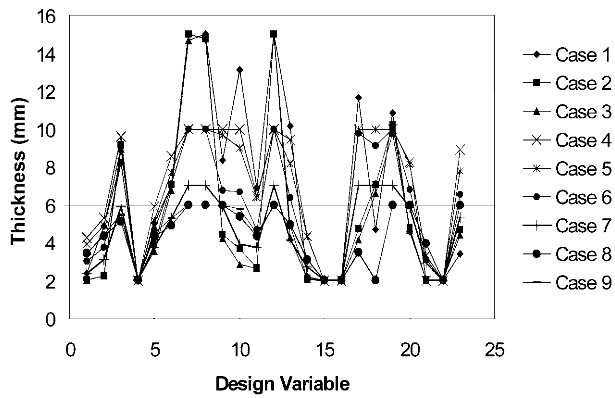

Fig. 10. Converged design variables.

pointed out that the thickness values shown in Fig. 8 are the initial values of 10 mm for the optimization run. The 30 mm values for the PCOMP entries include a 10 mm balsa core and two 10 mm composite face sheets.

Although the optimization method used in this design study, Nastran Solution 200, is capable of treating composite ply-angle variables – as was demonstrated in Botkin [4] – only woven cloth with a fixed, 90°, angle was used in an effort to reduce fabrication costs.

4.3. Design Concept Selection

Although Fig. 4 is referred to as a design concept, the parametric solid model can be thought of as a geometrical concept as opposed to a composite design concept. The goal of this design study is to use lower cost carbon fiber products such as chopped fiber and the less expensive *large* tow products. Estimated properties for these composites can be seen in Table 1 along with properties of all materials used for this study. The lower bound on all design variables was set at 2 mm which is considered to be the thinnest parts that can currently be molded using liquid molding processes. The cases are separated into three groups by upper bounds: 15, 10, and $<$10 mm. These thicknesses represent the succession of studies that took place in an effort to find a design with a suitably small maximum thickness. The mass histories of all cases and the thickness distributions are summarized in Figs 9 and 10, respectively.

It would be most desirable for a capability to exist that would determine an optimum composite concept rather than having to compare several selected concepts. Existence of such a capability is not known to the author.

4.4. 15 mm Upper Bounds

Case 1

The first case will be that of using all chopped carbon material with no sandwich construction. This would be considered to be the least expensive case using the cheapest material and having no core. Cores add to the material and processing cost and are difficult to mold. As with all cases there will be 23 design variables and a displacement constraint will be placed at the top of the shock tower to maintain the target stiffness shown previously. A preliminary analysis has shown that the initial design violates the displacement constraint by 33%. Figure 9 shows the mass history of this case. Although the initial stiffness target was *violated* at approximately 13.6 kg, the optimizer was able to find a design that satisfied the stiffness target at 6.2 kg, or 64% (6.2 kg/64%) mass reduction over the estimated steel mass. Considering this is a relatively low performance material, these results are remarkable. Figure 10 shows the design variable distribution of this case. The initial thickness of all design variables was 10.0 mm. Several of the variables terminated at their lower bounds of 2.0 mm which is considered to be the smallest thickness that can be reasonably molded using Resin Transfer Molding (RTM) or Structural Reaction Injection Molding (SRIM). Several variables, however, ended at the arbitrarily chosen upper bound of 15 mm. It should be pointed out that the variables which terminated at their upper bounds were more sensitive (in a mathematical sense) to the constraint than the mass. The remainder of the variables are more sensitive to mass than the constraint and hence provide the opportunity for mass reduction. A 15 mm thickness is considered to be a rather unrealistic value and leads to a conclusion that the material in those regions needs to be either higher performing or of a sandwich construction, which leads to Case 2.

Case 2
This case adds a 10 mm thick balsa core of 1.0 g/cm^3 (6.5 lb/cf) density to the top of the shock tower, i.e., variables 7 and 10 through 13 as shown in Fig. 6. Due to the added stiffness, the initial design in this case is 7.8% stiffer than the target value. Figure 9 shows the mass history of this case. Although the initial design was stiffer, the initial mass was higher due to the weight of the core and the added face sheet. In addition, even the final design was heavier than in Case 1 (6.62 kg/61.3%). As demonstrated in Botkin [4] when skin thicknesses are very large, sandwich construction may not be effective. Figure 10 also shows the variable distributions. Although several of the variables are driven to their upper bounds, most other variables are smaller than in Case 1.

Case 3
This case modifies the surface skin in the sandwich panel (top of shock tower) to a higher performing material. This will be a woven material in which the properties are shown in Table 1. It is assumed that this material will be made from the *low cost* 50K tow carbon fiber. Figure 9 shows the results of this case. As can be seen the final mass is only slightly larger (6.65 kg/61.2%) and the thicknesses have not been reduced, as was desired. Even though the elastic modulus is much greater for the weave, the shear properties are much lower.

4.5. 10 mm Upper Bounds

The following cases show the effect of reducing the upper bound on thickness to 10 mm. It is considered that 15 mm is excessively thick to be a reasonable construction. As one might expect the optimal mass increased in all cases.

Case 4
This case maintains the all-chopped carbon but with a core. (9.35 kg/45.4%).

Case 5
This case uses woven material in the *shock tower area* (9.09 kg/46.9%).

Case 6
This case uses two layers of woven material. The outer layer is 0°–90° and the inner layer is ±45° in order to improve the shear properties of the woven material. This construction had the desired effect of reducing the mass significantly from the other two 10 mm cases. (7.95 kg/53.6%).

4.6. <10 mm Upper Bounds

Case 7
This case is an extension of case 6 with a 20 mm core of 1.5 g/cm^3 (9.5 lb/cf) density and an upper bound on material thickness of 7 mm. The MTC body also used a 20 mm core but of aluminum honeycomb. This case resulted in a mass of 6.55 kg or 61.8% mass reduction over steel. This is a very reasonable design with maximum thicknesses well within the range of practical consideration.

Case 8
This case adds sandwich construction (a 10 mm balsa core) to design variable regions 17 and 18 shown in Fig. 6. The results of Case 7 indicated these regions to be at their upper bounds. Furthermore, as shown in Fig. 1, the shock tower also used sandwich construction in the side walls. Just as in Cases 6 and 7 woven material was used with the same lay-up. The results of this case were very encouraging in that an upper bound of 6 mm was obtained. Although the optimal mass is greater than in Case 7 (6.95 kg/59.4%), if maximum thickness is an issue, this case may be more desirable.

4.7. Strength Constraints

Case 9
In this case, two loading conditions are added to include strength constraints to the stiffness-only design (Case 8). The first load condition represents the average barrier loads from a 35 mph (56.3 km/hr) crash applied at the upper (10,000 N) and

lower rails (44,000 N), each side. The second loading condition represents a commonly-used 3g *pothole* load (6675 N) applied vertically at the shock tower. Constraints were imposed on stresses for the chopped carbon and failure indices [4] for the woven material. Since the tensile and compressive strengths of the chopped carbon were different, the more conservative limit of 150 Mpa was used as the stress constraint. For the failure index (Hoffman), a value of 1.0 was used as the constraint limit. The results of this case are shown as *Case 9* in Figs 9 and 10. Because the stiffness constraints are very severe for this lower-stiffness material, the stress constraints did not play a very important role in the design (7.1 kg/58.6%) compared to case 8. It is still, however, important to determine if the stiffness-only designs are realistic.

4.8. Case Summary

Case 7 appears to be the best design. This case uses the less costly chopped carbon in all areas except for the top of the shock tower where two layers of woven or stitched mat material is used in conjunction with a 20 mm balsa core. This type of reinforcement can also be obtained from the cheaper, large-tow carbon fiber and has been shown to have similar properties. The mass reduction is 61.8% over the steel structure compared with a 68% for the PNGV front structure that, as pointed out earlier, was fabricated from very costly aerospace-like materials and processes.

5. Summary and Conclusions

Parametric modeling coupled with structural optimization was used to carry out design studies on a lightweight body front structure. A tightly-coupled parametric structural design process was described in which no manual data preparation – beyond the parametric model description – is necessary. Parametric modeling was used to build several models of an automotive front structure concept which utilizes carbon fiber composite materials and the corresponding molding processes. Two alternative concepts were studied – only one concept was shown in this paper – which represent the structure as an adhesively bonded assembly of shells. Closed sections result from two pieces – an inner and outer. An ultra-lightweight body designed for PNGV was redesigned to include an all-composite front structure. Several carbon fiber material combinations were studied to determine mass reduction potential of certain types of carbon fiber products considered to be lower cost than typical carbon fiber materials used in the past. Structural optimization was used to compare several composite constructions for the design of the bonded front structure. Nine cases were studied using various materials and composite lay-ups. Mass savings estimates from 45% to 64% over steel were obtained. The most reasonable design consisted of a combination of chopped carbon fiber and woven carbon fiber and using a 20 mm balsa core in the top of the shock tower area. This design had a maximum thickness of 7 mm and a mass reduction over steel of approximately 62%. It was also found that adding strength constraints had very little effect on the designs.

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