2002-01-2050

# A Simple Approach to Selecting Automotive Body-in-White Primary-Structural Materials

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## ABSTRACT

A simple strategy for building lightweight automobile body-in-whites (BIWs) is developed and discussed herein. Because cost is a critical factor, expensive advanced materials, such as carbon fiber composites and magnesium, must only be used where they will be most effective. Constitutive laws for mass savings under various loading conditions indicate that these materials afford greater opportunity for mass saving when used in bending, buckling or torsion than in tensile, shear or compression. Consequently, it is recommended that these advanced materials be used in BIW components subject to bending and torsion such as rails, sills, "A-B-C" pillars, etc. Furthermore, BIW components primarily subject to tension, compression, or shear, such as floor pans, roofs, shock towers, etc., should be made from lower cost steel. Recommendations for future research that are consistent with this strategy are included.

## INTRODUCTION

Future body-in-white primary-structures will have to be designed according to a multitude of more complex, stringent, and often conflicting-objectives. These objectives include: providing higher levels of occupant protection; enhancing fuel economy and environmental friendliness through reduced mass and recyclability; reducing NVH through providing high attachment stiffness and noise abatement; providing a rigid foundation to bolster handling; maintaining or improving styling and packaging flexibility; ensuring reasonable longevity; and of course, offering all this with little or no increases in cost. No easy task.

The relative importance of each of these objectives will determine which materials are best suited for various parts of the BIW. An attempt is made herein to select materials for a highly idealized BIW primary-structure under the context of a hypothetical prioritization of these conflicting objectives. Although, all of the body-in-white objectives are critical to a product's success, it is necessary to prioritize them. For the purposes of this study, the priority is: first, cost, safety and mass reduction; second, handling and NVH; and third, styling flexibility and longevity. Recommendations are not meant to be specific to sedans, sports utility vehicles or "cross-over" vehicles. However, the idealized BIW considered here is a generic four door sedan.

In order to break down the problem of materials selection into manageable pieces, this study attempts to use a systems methodology.[1] n this spirit, the BIW (a.k.a. the overall system) is broken up into the following interdependent sub-systems: materials (steel, aluminum, polymer matrix composites, etc.); primary-structural components (B-pillars, floor pans, bumpers, body side apertures, etc.); joining elements (spot welds, laser welds, adhesives, screws, rivets, etc.); hang-on panels (hoods, doors, trunk lids, gas tank lid, etc.); and surface coatings (E-coat, galvanization, anodized material, paints, etc.). The first two sub-systems are the main focus of this paper.

## THE MATERIALS SUB-SYSTEM

Key materials properties to be considered for fulfilling the hierarchy of BIW objectives are cost per kilogram ($\$/kg$), density ($\rho$), yield and ultimate strength ($\sigma_y$ and $\sigma_{UTS}$), modulus ($E$), density-specific strength ($\sigma_{UTS}/\rho$), density-specific stiffness ($E/\rho$), cost-specific strength ($\sigma/\$$), cost-specific stiffness ($E/\$$) and elongation-to-failure ($\varepsilon$). Specific values for these properties for a variety of structural materials are listed in Table 1. These values are the basis for the materials

Table 1. Overview of Materials Properties

| | Raw materials cost $/kg | Density (g/cm3) | Yield Strength (MPa) | Elastic Modulus (GPa) | Strength/Density | Stiffness /Density | Strength/($/kg) | Stiffness/($/kg) |
|---|---|---|---|---|---|---|---|---|
| Steel | | | | | | | | |
| AerMet100 | 33 | 7,86 | 1724 | 200 | 219,3 | 25,4 | 52,2 | 6,1 |
| low range HSLA | 0,66 | 7,86 | 290 | 200 | 36,9 | 25,4 | 439,4 | 303,0 |
| high range HSLA | 0,66 | 7,86 | 503 | 200 | 64,0 | 25,4 | 762,1 | 303,0 |
| low range dual phase | 1,1 | 7,86 | 1020 | 200 | 129,8 | 25,4 | 927,3 | 181,8 |
| high range dual phase | 0,99 | 7,86 | 530 | 200 | 67,4 | 25,4 | 535,4 | 202,0 |
| low rangeTRIP | 0,99 | 7,86 | 379 | 200 | 48,2 | 25,4 | 382,8 | 202,0 |
| high range TRIP | 1,43 | 7,86 | 496 | 200 | 63,1 | 25,4 | 346,9 | 139,9 |
| Stainless steel | 1,65 | 7,86 | 276 | 193 | 35,1 | 24,6 | 167,3 | 117,0 |
| high range austenetic stainless | 1,76 | 7,86 | 552 | 200 | 70,2 | 25,4 | 313,6 | 113,6 |
| Aluminum | | | | | | | | |
| 6061-T6 | 3,19 | 2,77 | 241 | 70 | 87,0 | 25,3 | 75,5 | 21,9 |
| A356 | 2,42 | 2,77 | 207 | 70 | 74,7 | 25,3 | 85,5 | 28,9 |
| 7075-T6 | 3,41 | 2,77 | 441 | 70 | 159,2 | 25,3 | 129,3 | 20,5 |
| Magnesium | | | | | | | | |
| AZ91 | 3,52 | 1,77 | 159 | 45 | 89,8 | 25,4 | 45,2 | 12,8 |
| AM50 | 3,41 | 1,77 | 124 | 45 | 70,1 | 25,4 | 36,4 | 13,2 |
| AZ31-H24 | na | 1,77 | 221 | 45 | 124,9 | 25,4 | na | na |
| Titanium | | | | | | | | |
| 6V-4Al sheet | 74,00 | 4,46 | 947 | 115 | 212,3 | 25,8 | 12,8 | 1,6 |
| 3V-2.5Al sheet | 24,75 | 4,46 | 707 | 100 | 158,5 | 22,4 | 28,6 | 4,0 |
| Beryllium | 860 | 1,94 | 34,5 | 303 | 17,8 | 156,2 | 0,04 | 0,35 |

Table 1. Cont'd

| | Raw materials cost $/kg | Density (g/cm3) | Yield Strength (MPa) | Elastic Modulus (GPa) | Strength/Density | Stiffness /Density | Strength/($/kg) | Stiffness/($/kg) |
|---|---|---|---|---|---|---|---|---|
| Carbon Fiber | | | | | | | | |
| UD, Vf=70%, epoxy matrix | 8,5 | 1,60 | 1500 | 181 | 937,5 | 113,1 | 176,5 | 21,3 |
| UD, Vf=50%, vinyl ester matrix | 6,9 | 1,79 | 1662 | 117,2 | 928,5 | 65,5 | 240,9 | 17,0 |
| UD,Vf=50%, polypropylene matrix | 8 | 1,41 | 1641 | 117,2 | 1163,8 | 83,1 | 205,1 | 14,7 |
| SRIM UD Vf=47% | 8,2 | 1,44 | 1262 | 110,3 | 876,4 | 76,6 | 153,9 | 13,5 |
| SRIM 0/90 Vf=37% | 6,86 | 1,47 | 545 | 44,8 | 370,7 | 30,5 | 79,4 | 6,5 |
| RTM UD Vf=60% | 9,42 | 1,49 | 1627 | 131 | 1091,9 | 87,9 | 172,7 | 13,9 |
| RTM 0/90 Vf=50% | 8,56 | 1,44 | 531 | 51,7 | 368,8 | 35,9 | 62,0 | 6,0 |
| Chopped fiber, urethane, Vf=39% | 5,20 | 1,41 | 160 | 37 | 113,5 | 26,2 | 30,8 | 7,1 |
| Fiberglass | | | | | | | | |
| UD, Vf=45%, epoxy matrix | 2 | 1,80 | 1062 | 38,6 | 590,0 | 21,4 | 531,0 | 19,3 |
| RTM Iso VF=28% | 2,4 | 1,61 | 172 | 11,03 | 106,8 | 6,9 | 71,7 | 4,6 |
| RTM UD Vf=47% | 2,24 | 1,88 | 703 | 35,2 | 373,9 | 18,7 | 313,8 | 15,7 |
| RTM 0/90 Vf=47% | 2,24 | 1,88 | 372 | 24,8 | 197,9 | 13,2 | 166,1 | 11,1 |
| Chopped fiber, urethane, Vf=30 | 1,90 | 1,66 | 224 | 12,9 | 134,9 | 7,8 | 117,9 | 6,8 |
| Polymers | | | | | | | | |
| LCP | 26,4 | 1,61 | 110 | 11 | 68,3 | 6,8 | 4,2 | 0,4 |
| Nylon | 6,6 | 1,14 | 82,7 | 2,76 | 72,5 | 2,4 | 12,5 | 0,4 |
| ABS | 3,52 | 1,13 | 41 | 2,28 | 36,3 | 2,0 | 11,6 | 0,6 |
| Polyester | 2,2 | 1,34 | 55 | 2,4 | 41,0 | 1,8 | 25,0 | 1,1 |
| PET | 3,08 | 1,63 | 158 | 9 | 96,9 | 5,5 | 51,3 | 2,9 |
| Polyolifin | 2,86 | 1,19 | 32 | 3,03 | 26,9 | 2,5 | 11,2 | 1,1 |
| Polycarbonate | 3,74 | 1,20 | 65,5 | 2,4 | 54,6 | 2,0 | 17,5 | 0,6 |
| Polystyrene | 1,98 | 1,04 | 55 | 3,1 | 52,9 | 3,0 | 27,8 | 1,6 |
| PBT | 2,2 | 1,14 | 59 | 2,76 | 51,8 | 2,4 | 26,8 | 1,3 |

▨ = estimated value

selection calculations made in the Primary-Structural Components Sub-Systems sections (next section).

Most of the materials included in Table 1 are of current practical interest. However, for the sake of better defining the spectrum of available properties and cost, many materials currently either too costly or of insufficient mechanical properties (and likely to remain, in one or both categories, for some time) are listed. Beryllium, for instance, is included because its density specific elastic properties are greater than nearly any other material. However, at $858 per kilogram, it is far too expensive. The other end of the mechanical properties and cost spectrums are marked by polystyrene and ABS. Of materials lying near the more practical part of both the cost and properties spectrums, steel, aluminum, magnesium, fiberglass and carbon fiber composites are listed. Within each of these materials systems an attempt has been made to describe their individual spectrum of available properties. For example, under steels, properties for AerMet 100 (a nine component ultra-high strength steel) to low-alloy steels are listed. Likewise with carbon fiber and glass fiber polymer matrix composites, properties for variants ranging from unidirectional tape in an epoxy matrix to random chopped in a thermoplastic matrix are listed. Perhaps the latter materials are the only structural fiber composites that will be affordable to the mainstream auto industry for some time.

The spectrum nature of materials properties discussed above emphasizes a critical point regarding materials; like the BIW, they too are a system of interdependent sub-systems. Again, as with the BIW, manipulation of their interdependent sub-systems produces a spectrum of properties/performances. The number and complexity of sub-systems is dependent on the particular material. For example, some ultra-high strength steels can be broken down into the following subsystems:[1] the martensite matrix; strengthening dispersions (metal carbides); retained austenite dispersion; grain boundary mater; and grain refining dispersion. These sub-systems are manipulated through yet another sub-system of processing steps: alloying, solidification, solution treat, quenching, and tempering. If the quench step is performed at the wrong rate, the result could be not enough retained austenite and subsequent low toughness. If the tempering step is done at too low a temperature, the thermodynamic driving force for precipitation of metal carbides could be too low leading to a coarse dispersion and poor ductility. If lanthanum is left out during alloying, phosphorous may not be sufficiently gettered out of the grain boundaries which will lead to poor resistance against hydrogen embrittlement. And so on. Indeed, all of this is of gargantuan complexity and on the surface not seemingly of much value to a body engineer. So why write about it? To emphasize the extreme number of imaginable sub-system permutations and therefore point to the fact that table values make up only a small number of points on a multi-dimensional space of materials properties. The point of practical interest here is: never be satisfied with table values. Indeed, it is almost always appropriate to challenge material suppliers to tailor their product's properties for a given application. Ask for more!

In keeping with this philosophy of materials as complex systems, it is useful to represent a given material system's properties as regions on a graph. Ashby[2,3] provides an especially convenient method of doing so and "pseudo-Ashby diagrams" are presented for the specific (normalized) values listed in Table 1 in Figures 1 and 2. Defining the exact geometry of these regions is out of the scope of this paper, and admittedly, those shown are approximate. The conclusions from Figures 1 and 2 that deserve special emphasis are:

1. Within 4%, steel, stainless steels, magnesium, aluminum and 6V-4Al titanium all have the same density-specific stiffness.

2. The density-specific strength of the lowest-grade carbon fiber composites is about the same as medium-grade auto industry eligible steels. However, these same carbon fiber composites exhibit better density-specific stiffness than these metals.

3. Steel needs a yield strength greater than 586 MPa to beat most aluminum and magnesium alloys on a density-specific strength basis.

4. Low-grade fiberglass composites do not perform better than high- and medium- grade monolithic (single material) polymers.

5. On a cost-specific stiffness and cost-specific strength basis, automotive eligible steels are tough to beat. This is why they are so popular in the auto industry.

## THE PRIMARY-STRUCTURAL COMPONENTS SUB-SYSTEM

The mechanical performance of materials under loading conditions consistent with those endured by the primary-structural components (A,B,C-pillars, front and rear rails, roof, floor pan, bumpers, rear quarter panels, etc.) of the BIW are analyzed in this section. After determining which materials are most appropriate for various loading conditions, materials are recommended for use in primary-structural components. A full list of the components is given in Table 2 along with their loading/failure mode for a variety of BIW global loading conditions. Closure panels such as doors, fenders (front

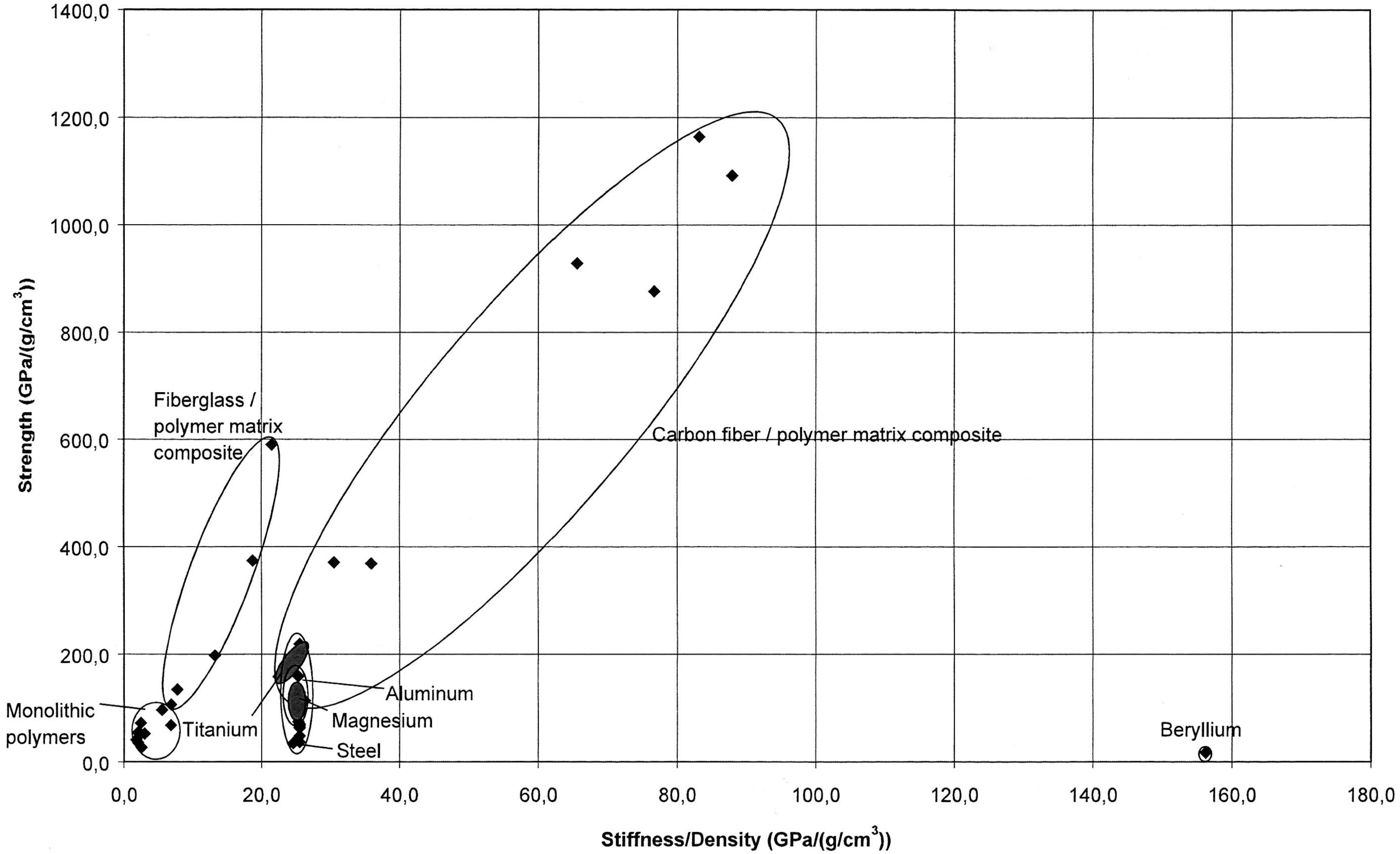


Figure 1. Density specific strength vs. density specific stiffness. Note that within 4% all of the metals (except 3-2.5 Ti) have the same density specific stiffness.

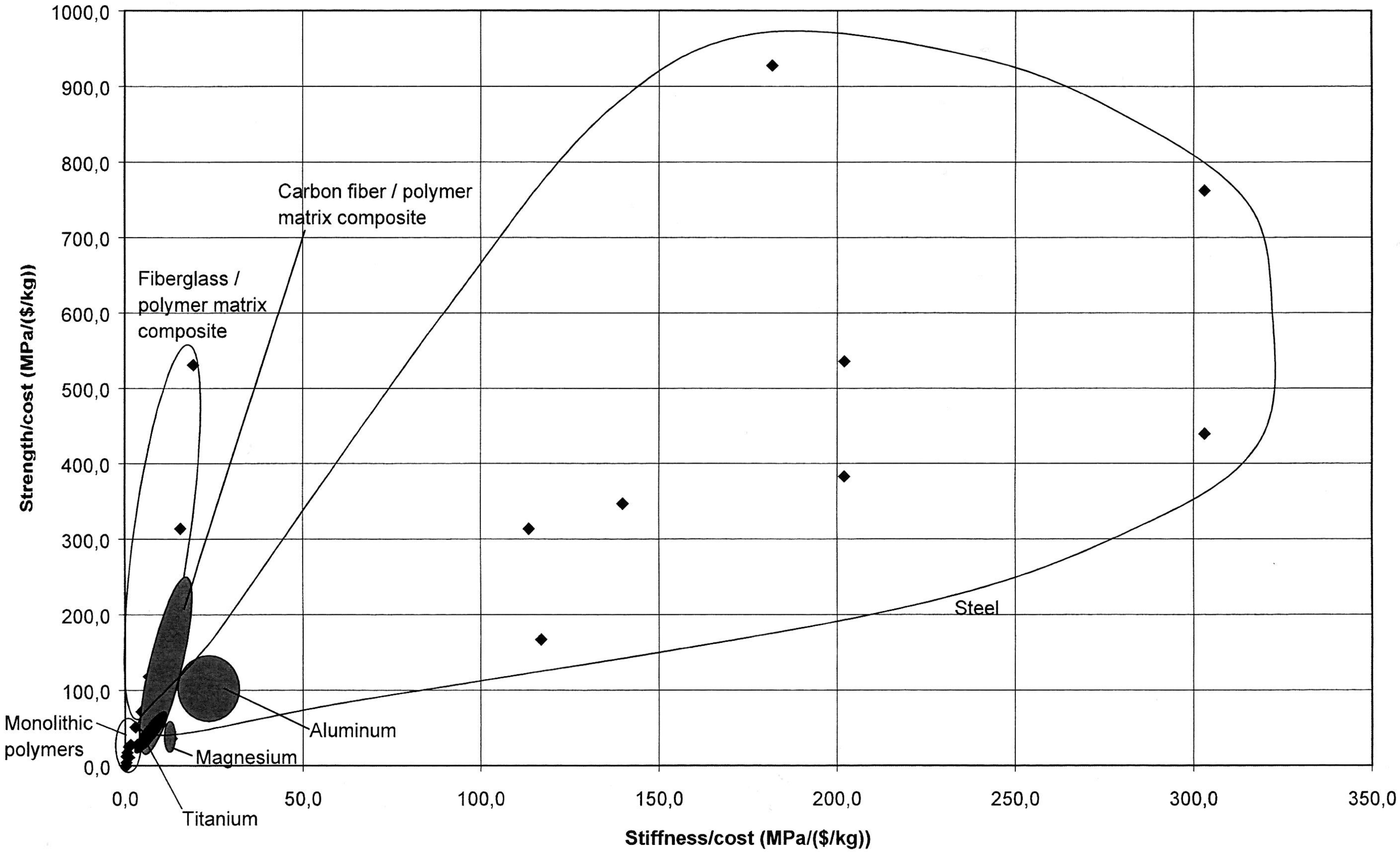


Figure 2. Cost specific strength vs. cost specific stiffness. Steel gives by far the most strength and stiffness for the money.

**Table 2. BIW parts and their loading under a variety of global loading conditions**

## Global BIW Loading

|  | Normal Driving Loads |  | Impact Loads |  |  |  |
|---|---|---|---|---|---|---|
|  | Bending | Torsion | Offset / Flat Front impact | Rear impact | Side impact | Roof-crush |
| **BIW Part** |  |  |  |  |  |  |
| Front bumper |  | B | C | C |  |  |
| Front rails | B | B | BU/C/B |  |  |  |
| Upper radiator support |  | B/C | C |  |  |  |
| Lower radiator support |  | TO | C |  |  |  |
| Shock towers | T/C | T/C/B | C |  |  |  |
| Wheel housings | T/C | T/C | C |  |  |  |
| Cradle / front cross member | T/C | TO | C/BU/B |  |  |  |
| Toe pan | T/C | T/C/S | B |  |  |  |
| Firewall | T/C | S | B |  |  |  |
| Plenum |  | TO | B |  |  |  |
| Floor pan | T/C | T/C | BU/C | BU/C | BU/C |  |
| Sills | T/C | B | BU/C | BU/C | B |  |
| A-pillars | T/C | T/C | B/C/BU |  | B | B |
| B-pillars | T/C | T/C | B | B | B | B/C |
| Roof | T/C | T/C | BU/C | BU/C | BU/C | B |
| Roof rails | T/C | B | BU/C | BU/C | B |  |

c=compression
t=tension
s=shear

b=bending
bu=buckling
to=torsion

**Table 2. Cont'd**

## Global BIW Loading

| | Normal Driving Loads | | Impact Loads | | | |
|---|---|---|---|---|---|---|
| | | | Offset / Flat | | | |
| BIW Part | Bending | Torsion | Front impact | Rear impact | Side impact | Roof-crush |
| Front & Rear header | | T/C | B | B | BU/C | B |
| Roof bow | | | | | BU/C | B |
| C-pillars | T/C | T/C | | B | B/C/BU | C/B |
| Shelf panel | | | | BU | C/BU | |
| Rear kick-up | T/C | T/C | BU/C | BU/C | BU/C | |
| tire tub | T/C | T/C | BU/C | BU/C | BU/C | |
| quarter panels | T/C | T/C | | C/BU | B | C/B |
| Rear shock towers | T/C | B/T/C | | B | | |
| Rear cross member | | TO | | B | C/BU | |
| Rear rails | T/C | T/C | | BU/C | B | |
| Rear bumper | B | B | | BU/C/B | | |
| Rear deck opening | | T/C | | C | | |

c=compression
t=tension
s=shear
b=bending
to=torsion
bu=buckling

and rear), hoods, trunk lids, fuel doors, windows, etc., are not considered here as primary-structure elements.

## MATERIALS SELECTION AND GEOMETRY

### The Realities of Mechanics

Consider a rectangular cross-sectioned solid, thin strip of material. This strip is subject to one of six loading conditions that will cause failure in tensile, compression, shear, bending, torsion or buckling. Listed in Table 3 are constitutive laws for mass reduction when a material 2 is substituted for a material *1*.[2-4] Listed are relations for each of these six loading conditions for both design-for-strength and design-for-stiffness scenarios. The same relations for a hollow tube rather than a strip are listed in Table 4. Note that for buckling, only the design-for-stiffness scenario is listed, because material thickness considered safe to support a compressive load can be far too thin to prevent buckling.

Select materials properties values from Table 1 are substituted into the constitutive relations. Listed next to all the constitutive relation in Tables 3 and 4 are the rankings for six different materials in order of decreasing opportunity for mass reduction. These rankings are made with respect to a relatively high-strength steel ($\sigma_y$ = 550 MPa). Values used for fiberglass and carbon fiber composites from Table 1 are "Chopped Fiber, urethane, Vf=30%" and "Chopped fiber, urethane, Vf=39%" respectively. Both data come from as-molded coupons and were chosen because they are the most likely to be affordable to the mainstream auto industry in the near future (10+ years). Aluminum and magnesium yield strength values used were 207 MPa and 138 MPa respectively, and for stiffnesses, 70 GPa and 44 GPa respectively.

### Assigning Materials to Primary-Structural Components

As mentioned previously, Table 2 lists the primary-structural components as well as their local loading (tension, compression, shear, etc.) under six global BIW loading conditions. Note the first two, global bending and torsion are relevant to normal driving, while the other four relate to impact. In conjunction with the overall system requirements listed in the introduction, the rankings in Tables 3 and 4 and the loading condition in Table 2, it is possible to select materials for primary-structural components. Note that components like sills, rails, pillars, etc. are approximated as tubes, and components like floor pans, roofs, tire tubes, shelves, plenums etc. are approximated as strips.

### Designing for Normal Driving Conditions

Under most driving conditions, the BIW is subject to global bending and torsion loads, and primary-structural components are typically designed for stiffness rather than strength. As can be seen in Table 2, such global loading conditions lead only to local tensile or compressive loads in most primary-structural components. Exceptions include rails, bumpers, sills and shock towers, which are subject to bending, and front cradles, rear cradles, radiator supports and plenums, which are subject to torsion.

Under the design-for-stiffness scenario, carbon fiber ranked first in opportunity for minimizing mass for all loading conditions. Consequently, it would make sense to build every primary-structural component from carbon fiber.[6-9] However costs would be too high.[9-15] A lower cost strategy is as follows. For the loading case tension/compression/shear loading, and under the design-for-stiffness scenario, carbon fiber ranks first, but steel ranks a relatively close second. Therefore, as the lowest cost material, steel should be used for components such as floor pans, roofs, shock towers, firewalls, etc, which, in this study, endure only tensile, compressive, or shear loads. In these applications, carbon fiber only offers a 3% greater opportunity for mass savings compared to steel, whereas in bending and torsion (strip only) applications, it offers a 68% greater opportunity for mass savings. Therefore, most components subject to bending or torsion should be in carbon fiber.

Another option for bending and torsion components would be the second ranking, but lower cost, magnesium.[5,16] In fact, bending / torsion components such as radiator supports and cradles have shapes that are more suited to cast magnesium than carbon fiber SMC. However, as magnesium has no fatigue limit,[17] in designing a given part to meet fatigue requirements, it is possible that the part becomes to thick too realize any mass saving. The possibility of this happening is related to stress concentrations within the part and microstructure. Prediction requires specific part modeling.

### Designing for Normal Driving Conditions and Impact

Maximizing mass savings opportunities and minimizing cost are more difficult when designing for impact than when designing for normal driving conditions. Instead of designing for stiffness, it is necessary to design for strength, and in every design-for-strength loading category in Tables 3 and 4, steel ranks last. Carbon fiber or fiberglass composite materials rank first or second, and magnesium ranks either third or second. Because of cost considerations, it is recommended that the most cost effective opportunity for mass savings is to use the more expensive materials in direct impact load paths only: in bumpers, rails, A-B-C pillars, roof rails, and sills. Moreover, it is recommended that these primary-structural components become the primary energy management structures and components such as floor

Table 3. Constitutive relations for mass reduction for materials strips

| **Loading** | | **Constitutive law for mass savings** | **Ranking** | **% of Steel's mass assuming $\sigma_y$=550 MPa** |
|---|---|---|---|---|
| **Tension/Compression /Shear** | | | | |
| | Design-for-strength | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\frac{\sigma_{y1}}{\sigma_{y2}}$ | 1. Fiberglass | 52 |
| | | | 2. Carbon fiber | 62 |
| | | | 3. Magnesium | 90 |
| | | | 4. Aluminum | 94 |
| | | | 5. Steel | - |
| | Design-for-stiffness | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\frac{E_1}{E_2}$ | 1. Carbon fiber | 97 |
| | | | 2. Steel | - |
| | | | 3. Magnesium | 100,1 |
| | | | 4. Aluminum | 100,7 |
| | | | 5. Fiberglass | 327 |
| **Bending** | | | | |
| | Design-for-strength | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{\sigma_{y1}}{\sigma_{y2}}\right)^{1/2}$ | 1. Fiberglass | 33 |
| | | | 2. Carbon fiber | 33 |
| | | | 3. Magnesium | 45 |
| | | | 4. Aluminum | 58 |
| | | | 5. Steel | - |
| | Design-for-stiffness | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1}{E_2}\right)^{1/3}$ | 1. Carbon fiber | 32 |
| | | | 2. Magnesium | 37 |
| | | | 3. Aluminum | 50 |
| | | | 4. Fiberglass | 53 |
| | | | 5. Steel | - |
| **Torsion** | | | | |
| | Design-for-strengh | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{\sigma_{y1}}{\sigma_{y2}}\right)^{1/2}$ | 1. Fiberglass | 33 |
| | | | 2. Carbon fiber | 33 |
| | | | 3. Magnesium | 45 |
| | | | 4. Aluminum | 57 |
| | | | 5. Steel | - |
| | Design-for-stiffness* | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1(1+\upsilon_2)}{E_2(1+\upsilon_1)}\right)^{1/3}$ | 1. Carbon fiber | 32 |
| | | | 2. Magnesium | 37 |
| | | | 3. Aluminum | 50 |
| | | | 4. Fiberglass | 53 |
| | | | 5. Steel | - |
| **Buckling** | | | | |
| | Design-for-stiffness | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1}{E_2}\right)^{1/3}$ | 1. Carbon fiber | 32 |
| | | | 2. Magnesium | 37 |
| | | | 3. Aluminum | 50 |
| | | | 4. Fiberglass | 53 |
| | | | 5. Steel | - |

*Assumes isotropic material, where $\upsilon$ is Poisons ratio. Values assume $\upsilon$=0.3 for all materials

Table 4. Constitutive relations for mass reduction for tubes

| **Loading** | **Constitutive law for mass savings** | **Ranking** | **% of Steel's mass assuming $\sigma_y$=550 MPa** |
|---|---|---|---|
| **Tension/Compression /Shear** | | | |
| Design-for-strength | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\frac{\sigma_{y1}}{\sigma_{y2}}$ | 1. Fiberglass | 52 |
| | | 2. Carbon fiber | 62 |
| | | 3. Magnesium | 90 |
| | | 4. Aluminum | 94 |
| | | 5. Steel | - |
| Design-for-stiffness | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\frac{E_1}{E_2}$ | 1. Carbon fiber | 97 |
| | | 2. Steel | - |
| | | 3. Magnesium | 100,1 |
| | | 4. Aluminum | 100,7 |
| | | 5. Fiberglass | 327 |
| **Bending** | | | |
| Design-for-strength | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{\sigma_{y1}}{\sigma_{y2}}\right)^{2/3}$ | 1. Fiberglass | 38 |
| | | 2. Carbon fiber | 41 |
| | | 3. Magnesium | 57 |
| | | 4. Aluminum | 68 |
| | | 5. Steel | - |
| Design-for-stiffness | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1}{E_2}\right)^{1/2}$ | 1. Carbon fiber | 42 |
| | | 2. Magnesium | 48 |
| | | 3. Aluminum | 60 |
| | | 4. Fiberglass | 83 |
| | | 5. Steel | - |
| **Torsion** | | | |
| Design-for-strengh | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{\sigma_{y1}}{\sigma_{y2}}\right)$ | 1. Fiberglass | 52 |
| | | 2. Carbon fiber | 62 |
| | | 3. Magnesium | 90 |
| | | 4. Aluminum | 94 |
| | | 5. Steel | - |
| Design-for-stiffness* | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1(1+\upsilon_2)}{E_2(1+\upsilon_1)}\right)$ | 1. Carbon fiber | 97 |
| | | 2. Steel | - |
| | | 3. Magnesium | 100,1 |
| | | 4. Aluminum | 100,7 |
| | | 5. Fiberglass | 327 |
| **Buckling** | | | |
| Design-for-stiffness | $\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1}{E_2}\right)^{1/2}$ | 1. Carbon fiber | 42 |
| | | 2. Magnesium | 48 |
| | | 3. Aluminum | 60 |
| | | 4. Fiberglass | 83 |
| | | 5. Steel | - |

*Assumes isotropic material, where $\upsilon$ is Poisons ratio. Values assume $\upsilon$=0.3 for all materials pans, roofs, shock towers, firewalls, etc., become ancillary. Accordingly, and as discussed in the previous section, it is recommended that floor pans, roofs, shock towers, and firewalls be made of steel. Finally, attempting to use fiberglass as a low cost alternative to carbon fiber is not recommended because it ranks low in all design-for-stiffness loading conditions.

A list of recommended materials and processing routes for all primary-structural components is tabulated in Table 5 and shown graphically in Figure 3.

Many concerns have arisen regarding the performance of composite impact structures.[18-24] Certainly, composites absorb energy by a different mechanism than metals. Metals absorb energy via plastic deformation, while composites absorb energy through splintering, functional sliding between fibers and matrices, and the subsequent creation of surface area/energy. A large body of data indicates the greater effectiveness of the latter mechanism. Recognize that all Formula 1 and CART racing cars rely on composite crash structures.[19]

### GAUGE THICKNESS

Up to this point, it has been assumed that enough macro-geometrical control is available in all of the materials considered above, such that superfluous material is eliminated, and every infinitesimal parcel of material is stress to near its limit (but not beyond). The mass/strength balance would indeed be optimized. However, this assumption is not realistic and superfluous mass will always be present. The amount of superfluous mass is design specific and can not be meaningfully estimated here. Nevertheless, as a first approximation, gauge thickness can be estimated and compared against current processing capabilities. Based on sheet steel gauges used on rails and sills on current Chrysler Concord vehicles, carbon fiber SMC parts would have to be a minimum of 1.5 mm thick. Internal research at DaimlerChrysler AG indicates that such thickness is possible with SMC but mass-volume processing techniques are not yet available. Cast magnesium would have to be ~ 2 mm thick. Given the current high-pressure die-casting capabilities of magnesium, this would be a challenge. Finally, mass efficient substitution of either DP (dual phase) or TRIP steels for the standard steel used in rail or sill application would require sheets 0.25 to 0.5 mm thick. This is likely too thin to handle off-axis loads. Moreover, NVH would likely suffer due to low attachment stiffness. If steel is to be used in such thin gauges, it may be advantageous to use the steel/polymer/steel sandwich materials that are currently available.

## OVERVIEW AND SUGGESTIONS FOR FUTURE WORK

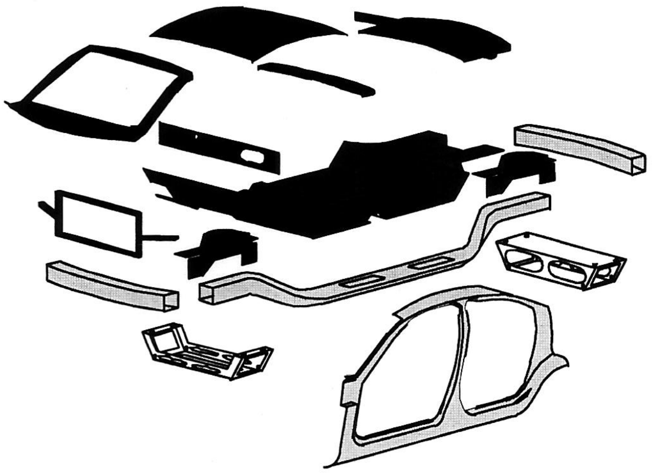
A hierarchy of body-in-white (BIW) performance objectives has been defined and strategy for achieving these objectives through materials selection has been described. As the first step in achieving this, a database of structural materials properties for materials potentially applicable in BIWs has been assembled. This database attempts to define a multidimensional space with axis of cost, density, strength, and stiffness. Moreover, in order to emphasize that within each materials system (steel, aluminum, magnesium, fiberglass, etc.) there is an equivalent multidimensional space, the database is represented in a graphical format where a region rather than a point is used to denote a materials system. The next step has been to break up the BIW into primary-structural components and define their local loading case (tension, compression, bending, torsion, etc.) for global loading conditions relevant to both normal and impact scenarios. Constitutive relations consistent with design-for-strength and design-for-stiffness scenarios for each of the local loading cases were defined and materials ranked for potential for mass reduction. From these rankings it is clear that the mass/strength/stiffness balance can best be optimized when the entire vehicle is made from carbon fiber composites. However, as cost is of highest priority, this is not possible. Consequently, it is recommended to use carbon fiber to form a one-piece rail and sill structure, and to use steel in the floor and roof structures where carbon fiber would be of the least use. The strategy is to use the expensive material where will be of most benefit.

In order to get an approximation of how effective this strategy is at fulfilling the prioritization of BIW objectives listed in the Introduction, a rough finite element model was constructed applying the materials selection in Table 5 to the Chrysler Concorde. Except for gauge thickness, part geometry was not changed. Without getting into too much detail, the results indicate that a 40% reduction in mass is possible but at a 20% decrease in static bending and torsion stiffness. With respect to these metrics, the prioritization has been met because mass reduction is prioritized higher than stiffness. However, materials costs are estimated to increase by 96% and this does not include extra processing costs associated with composites. Surely, this is not consistent with the prioritization of cost. Indeed, under today's construction paradigm of welded steel stampings, cost parity while using composite materials or non-ferrous metals poses a formidable challenge.

Table 5. BIW primary structural components and recommended materials

| BIW Part | Recommended Material | Processing Route |
|---|---|---|
| Front bumper | Low-grade carbon fiber composite | Fabric stamping or RTM |
| Front rails | Low-grade carbon fiber composite | Fabric stamping or RTM |
| Upper radiator support | Magnesium | Cast |
| Lower radiator support | Magnesium | Cast |
| Shock towers | Steel | Stamp |
| Wheel housings | Steel | Stamp |
| Cradle / front cross member | Aluminum | Cast |
| Toe pan | Steel | Stamp |
| Firewall | Steel | Stamp |
| Plenum | Magnesium | Cast |
| Floor pan | Steel | Stamp |
| Sills | Low-grade carbon fiber composite | Fabric stamping or RTM |
| A-pillars | magnesium inside/carbon outside | SMC |
| B-pillars | Low-grade carbon fiber composite | SMC |
| Roof | Steel | Stamp |
| Roof rails | Low-grade carbon fiber composite | SMC |
| Front & Rear header | Magnesium | Cast |
| Roof bow | Steel | Stamp |
| C-pillars | magnesium inside/carbon outside | SMC |
| Shelf panel | Magnesium | Cast |
| Rear kick-up | Steel | Stamp |
| tire tub | Steel | Stamp |
| Rear shock towers | Steel | Stamp |
| Rear cross member | Aluminum | Cast |
| Rear rails | Low-grade carbon fiber composite | Fabric stamping or RTM |
| Rear bumper | Low-grade carbon fiber composite | Pultrusion |
| Rear deck opening | Steel | Stamp |

RTM = Resin Transfer Molding
SMC = Sheet Molding Compound



▨ Low-grade carbon fiber composite

■ Steel

■ Cast magnesium

□ Cast aluminum

Figure 3. The primary structural components and recommended materials.

Costs for composites materials will continue to decrease. However, whether these cost reductions will ever be able to offset a price increase of 96+%, maybe unlikely. Consequently, parts consolidation strategies need to be employed. As mentioned previously, rail and sill structures should be combined. Roof header and A- and C- pillars can likely be combined via large castings. The concept of combining radiator supports and headlight buckets into a single casting is not new. Finally, as described in Reference 25, a floor pan, a rear kick-up and a tire tub structures can also perhaps be combined into an ultra-large casting. As it is recommended herein that these pieces be made from steel, research into making cost effective ultra-thin walled steel castings[26] should be pursued.

Aside from this very serious issue of cost, at least one more severe challenge exists with the strategy described here. Construction of multi-material BIWs involves the combination of disparate thermal expansion rates and subsequent residual stresses. Indeed, carbon fiber composites can have an order of magnitude different coefficient of thermal expansion than steel. This means that in climates which experience extremes of cold and hot, loosening of bonds or even catastrophic failure could occur. However, this joining problem is likely not insurmountable. Structural bonding[27-31] has potential because adhesives typically have lower modulus than the material being joined and can therefore reduce stress concentrations. In addition, a large body of experience and success exists in the similar problem of joining metals to ceramics for high temperature applications. A typical solution is to sandwich a layer of material with an intermediate thermal expansion coefficient between the ceramic and the metal. The result is a reduction in the stress concentration at the interfaces between the three materials and an increase in resistance to failure from thermal cycling. So, as a final recommendation, a similar strategy for joining polymer matrix composites and metals should be investigated.

## ACKNOWLEDGMENTS

Thanks to Saad Abouzahr, Bob Schoen, Paul Belanger, John Fillion, Tom Hildebrandt, and Andy Rich of DaimlerChrysler for technical discussions leading to this paper's conclusions, as well as Jeremey Goddard of Visteon Corp. for proofreading the manuscript.

## REFERENCES

1. G.B. Olson, "Materials Design: An Undergraduate Course," *Proceedings for the Morris E. Fine Symposium*, ed. P.K. Liaw , J.R.Weertman, H. L. Marcus and J. S. Sentner, The Minerals, Metals and Materials Society, 1991.M.F.

2. M.F. Ashby, "Materials and Shape," *Acta Metall. Mater.*, 39[6], p. 1025-1039, 1991.M.F.

3. M.F. Asby, "Materials Selection in Conceptual Design," Proceedings from the Ashby Symposium on Materials Design, ASM World Materials Congress, Chicago, IL, 1988.

4. F.B. Beer, and E.R. Johnson, "Mechanics of Materials," 2nd Edition, McGraw-Hill, NY, NY, 1992.

5. A.A. Luo, "Materials Comparison and Potential Applications of Magnesium Automobiles," *Magnesium Technology 2000*, Editors H.I. Kaplan, J. Hryn, and B. Clow, TMS, p. 89-97, 2000.

6. J.A. Bennet, and M.F. Nelson, "An Optimization Capability for Automotive Structures," SAE Paper# 790972, p. 1-9, 1979.

7. R.E. Bonnet, R.A. Carpenter, D.G. Loosle, and R.W. Provancher, "Structural Composites in a Lightweight Body Structure," *Proceedings from the International Body Engineering Conference,* p38-44, 1995.

8. D. A. Cedar, "Fabrication and Assembly of a Graphite Fiber Reinforced Plastic Vehicle," SAE Paper# 790029, p. 1-14, 1979.

9. R. Miel, “BMW Puts New Design Idea on Carbon-Fiber Diet,” *Automotive News*, 10/23, p. 36D-36F, 2000.

10. J.R. Dieffenbach, “Challenging Today's Stamped Steel Unibody: Assessing Prospectus for Steel, Aluminum and Polymer Composites,” *Proceedings from the International Body Engineering Conference,* Stuttgart, Germany, p. 1-6, 1997.

11. J.R. Dieffenbach, and A.E. Mascarin, “Body-in-White Material Systems: A Life-Cycle Cost Comparison,” *J. of Metals*, 6, p. 16-19, 1993.

12. T.L. Gibson, “Life Cycle Assessment of Advanced Materials for Automotive Applications,” SAE Paper# 2000-01-1486, p. 1-10, 2000.

13. 1A. E. Mascarin, J.F. Wzorek, G. Rossi, and V. Brachos, “Development of a Manufacturing Strategy for Moderate Volume Production of a Composite Vehicle Structure,” SAE Paper # 982400, *Proceedings from the International Body Engineering Conference,* Detroit, MI, p.1-6, 1998.

14. A. E. Mascarin, J.F. Wzorek, G. Rossi, and V. Brachos, “Development of a Manufacturing Strategy for Moderate Volume Production of a Composite Vehicle Structure,” SAE Paper # 982400, *Proceedings from the International Body Engineering Conference,* Detroit, MI, p.1-6, 1998.

15. A.H. Rothacker, and G.A. Pelts, “High Productivity/Low Cost Manufacturing Approach to SRIM Molding,” SAE Paper # 980998, p. 1-3, 1998.

16. S. Durrani, “Optimizing Convertible Automotive Design Through the Use of Magnesium,” SAE Paper# 930411, p.1-6, 1993.

17. G.E. Dieter, “Mechanical Metallurgy,” 3rd Ed., published by McGraw-Hill Book Company, New York, NY, 1986.

18. J. Brandt, K. Drechsler, and M. Nohr, “Crush Behavior of 3D Textile Structural Composites,” *Conference Proceedings from the International Body Engineering Conference*, p. 105-111, 1997.

19. D.A. Doi, R.A. Jeryan, H.F. Mahmood, J.S. Akhtar, and M.P. Stephens, “Composite Impact Analysis of Race Cars – Technology Transfer to Passenger Car Development,” SAE Paper# 983092, *Proceedings from the Motorsports Engineering Conference and Exposition*, Dearborn, MI, p. 1-5, 1998.

20. V. Lakshminarayan, G.K. Balagopalan, M. Yu, and S. Chen, “Applications of CAE Nonlinear Finite Element Analysis in the Crashworthiness Development of a Vehicle with Aluminum and Composite Structures,” *Proceedings from the International Body Engineering Conference,* p. 123-130, 1995.

21. H-K. Lee, and S.Simunovic, “Constitutive Modeling and Impact Simulation of Random Carbon Fiber Polymer Matrix Composite for Automotive Applications,” SAE Paper # 2000-01-1574, p. 1-6, 2000.

22. R. Maruthayppan, P Balakrishnan, V. Gupta, and A.W. Chan, “A Comparison of Thermoplastic Composites vs. Conventional- Steel Instrument Panel Systems for Side-Impact Energy Management,” SAE Paper # 980962, p. 1-8, 1998.

23. M. Phillips, L. Patberg, R. Dittmann, and H. Adam, “Structural Analysis and Testing of Composites in Automotive Crashworthiness Application,” SAE Paper # 981140, p. 97-100, 1998.

24. D.W. Schmueser, L.E. Wickliffe, and G.T. Mase, “Front Impact Evaluation of Primary Structural Components of a Composite Space Frame,” SAE Paper # 880890, p. 57-65, 1988.

25. T.N. Meyer, M.J. Kinosz, E.M. Bradac, M. Mbaye, J.T. Burg and M.A. Klingensmith, “Ultra Large Casting to Produce Low Cost Aluminum Vehicle Structures,” SAE Paper # 1999-01-2252, p. 1-6, 1999.

26. G.Dixon-Chandley, J.A. Redemske, J.N. Johnson, R.C. Shah, and P.H. Mikkola, “Counter-Gravity Casting Process for Making Thinwall Steel Exhaust Manifolds,” SAE Paper# 970920, p. 145-152, 1997.

27. R.H. Beck Jr., and D.A. Yurek, “Automotive Structural Bonding,” SAE Paper# 750077, p. 1-14, 1975.

28. H.J. Cornille, “The Contribution of Structural Adhesive to Body Structure NVH,*” Proceedings from the International Body Engineering Conference*, p. 29-39,1994.

29. M.Fu, and P.K. Mallick, “Performance of Adhesive Joints in an Automotive Composite Structure,” SAE Paper# 2000-01-1131, p. 1-9, 2000.

30. L.J. Hart-Smith, “Adhesive Bonding of Aircraft Primary Structures,” SAE Paper# 801209, p. 1-15, 1980.

31. J. L. Minichelli, “Bonding Automotive Galvanized Sheet Steel with One-Part Zinc Activated Acrylic

Structural Adhesives," SAE Paper # 910507, p. 1-6,
19.