Cost Effective Design of Composite Structure for Automotive Applications

by

Newton Eliot Mack
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Author ....
Newton Eliot Mack
Department of Mechanical Engineering
May 20,1996

Approved by ....
Robert Faiz
Technical Supervisor
Draper Laboratory

Certified by ....
Daniel E. Whitney, Ph.D.
Thesis Supervisor

Accepted by ....
Ain A. Sonin, Chairman
Departmental Graduate Committee

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Abstract

Successful use of composite primary structure in the automotive world is dependent on cost and performance criteria. The focus of this thesis is on the decision making process involving both of these factors for automotive applications. Emphasis was placed on composite materials and fabrication processes that can be used for medium volume (500-100,000 components/year), high performance, low cost components.

A case study was made involving a 4 passenger composite electric vehicle. The cost and performance tradeoffs resulted in a vehicle using current thermoset technology and resins that provided a body-in-white weight reduction of 192 lbs or 35% over an average production vehicle at a cost increase of $438 or 39%. Based on volume price projections for thermoplastic matrix composite material, a vehicle could be constructed that achieved similar weight loss at a 17% cost increase, or $212.

These prices are achievable at relatively low production levels of 20,000 vehicles/year, making the selected composite manufacturing methods ideal for the initially low-volume market of electric vehicles.

Thesis Supervisor: Dr. Daniel E. Whitney, Senior Research Analyst, Mechanical Engineering

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Chapter 1

Introduction

1.1 Driving Forces

Personal motor vehicles are estimated to cause nearly 30% of the carbon dioxide emissions pollution in industrial countries, and are the primary cause of the smog problem in many US cities[1]. The problem is steadily increasing as more and more vehicles are added to the active fleet, and will become even more critical when the large populations of developing countries mobilize. Vehicle emissions have decreased markedly over the previous decades due to extensive refinement of internal combustion engines, but the problem remains.

One solution to the urban pollution problem is the use of electric vehicles. The range of an electric vehicle between required battery charges is one of the most critical factors required for public acceptance[2]. The main approaches available for increased mileage are an increase in the energy storage density of the batteries or a decrease in the vehicle's mass. Extensive research has taken place in the field of increasing energy density of batteries and has produced several varieties of improved chemical storage, but with a high associated cost.

Relatively little successful effort has been directed, however, to the weight savings possible in vehicles by using composite primary structure in moderate volume commercial applications. This approach offers the approach of weight savings as well as the promise of lower tooling costs, due to part consolidation and the elimination of multiple dies for a single part, and is the focus of this study.

Non-composite alternatives exist for lower weight in vehicles. Recently, a consortium of automotive manufacturers and steel producers created the Ultralight Steel Auto Body concept, which uses higher strength steels and increased use of innovative steel manufacturing techniques such as hydroforming to more efficiently meet structural requirements. In order to compare the weight of various vehicle body material choices, the 'body-in-white' weight is used. A body-in-white in this case is the bare primered frame and does not include 'closure panels'--doors, hood, front fascia, front fenders, or rear deck lid--which are non-structural and can be made from a variety of materials. Whereas a typical body-in-white for a contemporary sedan has a weight of about 598 lbs, constituting 20-25% of the vehicle's total weight, the ULSAB concept vehicle body-in-white for the same configuration has a weight of 452 lbs[3]. This approach has the advantage of using steel's large existing technology base, including its complete recycling and high volume processing systems. Disadvantages include requiring multiple dies for each part and a large overall number of parts and hence dies. Die costs average $200,000-$600,000 per die, with 3-4 dies needed per individual part, causing the up front capitalization costs to be very high[4]. Combined with the (for now) relatively limited nature of the electric car market, it is very difficult to foresee sufficient sales of an ultralight steel electric vehicle to pay for such a high startup cost.

Aluminum vehicles have also been studied. Audi of Germany has extensive efforts under way in aluminum vehicle structures, and some welded aluminum structures have been incorporated into the next model of the Corvette. The principal problems inherent with aluminum are joining related. Spot welding is typically used in assembly of steel bodied automobiles. In automotive grade steel, spot welding produces a strong joint and does not appreciably degrade the performance of the steel alloy. Weldable aluminum alloys of sufficient strength for use in ultralight vehicle design achieve their strength by cold working or by solution heat treating (heating the material up above 1000° F, quenching in water, and then aging the material for several hours at 300-400° F.) Welding these alloys typically causes their yield strength to drop by nearly half in the heat-affected zone, negating much of the weight savings gained by their use.

Several other fundamental problems inhibit the adoption of aluminum. The strongest of the generally available sheet aluminum alloys are not weldable. Structural bonding and riveting must be used instead, processes that are well established in the aircraft industry, but have not achieved widespread use in automotive primary structure. This is largely due to the relative slowness of the surface preparation/bonding process (in comparison to spot welding) and to the occasional unpredictability of the bond strength. Aluminum does not have the potential of tooling savings that can be expected from composites. Like steel, it requires multiple strikes to achieve a finished shape in aluminum, thus requiring multiple dies for a single part. Aluminum does have an extensive recycling infrastructure in place and can achieve Class-A surface finish, which is required for exterior panel applications. Recycling aluminum, however, is more difficult than recycling steel; common adhesives, paints, steel fasteners, and chemicals used in automotive applications can contaminate aluminum recycle melts and cause the recycled material to be unusable for primary use applications.

Composites offer some advantages over the previous approaches, and this study has grown out of an effort to explore the possibilities of using composites to address electric vehicles' unusual combined requirements of ultra light weight, low cost, and relatively small (500-100,000 vehicles/year) manufacturing runs.

1.2 NAVC

The NAVC (Northeast Alternative Vehicle Consortium) was created to further alternative energy technologies in the Northeast. One of the NAVC's efforts is the promotion of small, independent, entrepreneurial electric vehicle manufacturing companies. This thesis was originally funded out of such an effort.

The purpose of this study is twofold. The Big Three are all undertaking extensive EV development projects, and the question arises whether it would be simpler to wait for them to finish development. However, the automotive companies have a large amount of time and effort invested in the development of steel bodied vehicles and are understandably reluctant to place a composite structured vehicle into full production. One goal of this thesis is to demonstrate that ultralight composite vehicles are indeed economically feasible to manufacture.

The other purpose of this study is to demonstrate that a smaller independent manufacturer can successfully build and sell composite electric vehicles at a profit, and to provide something of a blueprint for doing so[5]. For this reason, all analysis tools used in this study are PC based, allowing groups with limited resources to replicate the results achieved here.

1.3 Why Composites?

Composite materials are more expensive than their homogenous counterparts. The automotive industry is largely cost-driven. There must then exist considerable reason to study the use of composite materials in automotive structural applications. There are two factors that make the future of composites promising: low weight and low startup costs.

Composites, when used properly, can provide equal performance at substantially reduced weight when compared to aluminum, steel, and most isotropic materials. The results of this study indicate that a vehicle body based on fiberglass composites can provide weight savings of 35% over a standard steel body. These savings are multiplied further by associated reduction in brake size, engine size, and drivetrain requirements.

Composites also allow for lower startup costs than steel or aluminum stamping. For example, many dozens of parts, each requiring several dies to achieve final shape, are required to make up a typical vehicle's chassis. As mentioned previously, each cast iron or cast steel die averages $200,000-$600,000. In contrast, the composite vehicle used as a case study here has only 10 parts in its structural chassis assembly, and as some of these parts are duplicates, only requires 6 mold sets due to fore/aft symmetry.

Composite materials also allow, at least initially, the use of less expensive mold materials. Epoxy based tooling is in extensive use in the aircraft industry, but its extremely limited useful life (typically several dozen parts) makes it an unattractive choice for even the low end of automotive scale production. Steel molds are still required for high volume, extended production runs, and when chrome plated provide the best release surface, surface finish, and durability of any mold. Steel molds are used in this study, as for the volumes and production runs encountered they are highly suggested, but for initial production volumes even lower than 500/year, aluminum molds become an attractive alternative and can be plaster cast to required dimensions with tolerances of $\pm$0.025 in.[6] and at a much lower cost than steel molds. The plaster molds can be themselves cast from handmade prototype tools or CNC machined with extremely inexpensive (less than $1500) computer controlled routers[7]. This degree of inaccuracy is insufficient for high volumes due to the cost of rework, but at the low volume, initial production levels a startup company is capable of, cast aluminum molds seem a viable alternative. Many cost studies have demonstrated that at low volumes, composite components enjoy a cost advantage over steel components[8] due to the lower capitalization and tooling costs.

In large scale (over 100,000 vehicles/year) production, the situation is somewhat different. When the production volume is sufficiently high enough to make the capital cost per part very low, the material cost dominates the component price. Despite the need for multiple die sets per part, steel's lower material cost, at $0.35/lb[9], becomes economically competitive when compared to fiberglass at $1.25/lb and polyester resin at $1.23/lb for a combined (weight averaged, 55% volume fraction, 72% weight fraction) total of $1.24/lb[10]. Because of this, at higher volumes, or over around 100,000 units annually, steel becomes more cost competitive[11].

This indicates why the auto makers have generated high resistance to introducing low volume, low cost steel body electric vehicles--at the initial low volumes expected for sales of electric vehicles, the market size is insufficiently large to pay for the tooling and startup technology around which their system of manufacturing is based. Electric vehicles are thus the province of smaller manufacturing firms until the market is large enough to justify the startup expense for steel manufacturing.

1.4 Purpose and Overview

There exists the need for a thorough study of the basic decisions and problems that would be encountered by a small firm attempting to produce an commercially successful composite electric vehicle. Possible methods for construction with composite materials vary more widely than with metallic construction, and the performance and cost of the vehicle will vary widely with the choice of processing technique. This thesis will examine viable cost and weight targets for a composite electric vehicle, the manufacturing and processing options available, and the cost/weight tradeoffs inherent in the selection of manufacturing process.

Chapter 2 will provide an overview of previous attempts at commercial composite vehicles and discern why they were not successful in the marketplace. Two market surveys conducted to determine public factors in acceptance of electric vehicles will then be reviewed, and the results used to set weight, cost, and performance targets for the composite electric vehicle. Chapter 3 will introduce the structural and cost models used to develop the design and manufacturing process of the composite vehicle. The process of decomposing the overall performance targets into individual component design parameters, as well as the various manufacturing process tradeoffs, is covered in Chapter 4. Chapter 5 deals with the development and successful test of the crash control structure. Chapter 6 pulls the results of the previous chapters together with joining models and from there develops the projected construction cost of the composite structure, and compares it to current and proposed steel bodied vehicles. Chapter 7 summarizes the efforts and provides directions for future work.

Chapter 2

Background

2.1 Previous Attempts At Composite Vehicles

The concept of constructing a lightweight composite vehicle is not a new one. Various attempts at partially composite or fully composite vehicles have been prototyped several times, with some models introduced to the market. None have been commercially successful. This has typically been due to improper use of the composite material or improper choice of manufacturing process.

The Consulier GTP sports car was the most recent all composite vehicle to be introduced to the market. It was constructed by a hand lay-up vacuum bagging method with fiberglass cloth and epoxy resin over polyurethane foam cores. The vehicle shell/chassis weighed 275 lbs out of the mold, and resulted in a finished vehicle weight of between 1850 and 2150 lbs with a Chrysler 4 cylinder engine. These vehicles were successfully crash tested and passed NHTSA, EPA, and DOT tests. Price was set at $52,500[12]. The vehicle was a marketplace failure, as extensive hand labor costs drove the production costs high and the vehicle possessed relatively unattractive styling. The car was, however, capable of sub-14 second quarter mile times and 34 mpg on the highway[13], and unusual combination.

Another attempt at a fiberglass composite vehicle structure prototype was conducted by Ford. A fiberglass recreation of a Taurus sedan was constructed by using the existing metal body structure as a die model for fiberglass molds[14]. The laminates were created using resin transfer molding, vinylester resin, and E glass in oriented, random chopped, and continuous forms. This vehicle achieved a weight reduction of 71 lbs, but it was noted by the constructors that they had not used the material in the most rigorous manner possible and that 250 lbs of weight reduction could be achieved in a more through exercise.

The common features of the attempts made by large scale automotive manufacturers in constructing composite vehicles is their tendency to try to construct them in a fashion similar to steel cars; that is to say with materials that are mostly randomly oriented, with low fiber volumes, so that their properties become isotropic and the directionality and stampability of the material is not an issue. However, composite materials, when not used in an oriented manner with high volume fractions (more than 50%), display little if any performance improvement over conventional materials and thus the impetus for their use in the first place is lost. Also, the auto manufacturers tend to attempt to replace steel components with composite components on a part-by-part basis, which further lowers performance as the high stress concentrations in composite materials from bolted attachments and the subsequent overdesign necessary to prevent failure remove much of the performance improvement. Intelligent composite construction uses component consolidation up to the point where part yield and molding complexity begin to suffer, and then joins the components together using distributed area fastening (adhesive bonding or thermoplastic welding.)

The common features of the attempts previously made by independent composite manufacturers are intelligent use of the material properties and use of fabrication techniques ill suited to high volume and low cost. For example, the Consulier used a molding technique that produced the entire body in one piece, but caused problems due to the high degree of hand labor required to mold the complex component. In the aerospace sphere, these slow, labor intensive production techniques are viable. This is not true for automotive production scales and markets. The GM Ultralight used a similar hand labor based layup technique, but substituted the fiberglass material with carbon fiber, which caused both excessive material costs and hand labor costs.

No effort has yet been made that combines proper design and use of composite materials with the processing techniques necessary to achieve production scales.

From these attempts it can be concluded that effective weight savings using inexpensive composite materials will only arise from the proper use of those materials; high volume fractions (50% +) and oriented fiber layups must be used instead of low volume fraction, randomly oriented and chopped fiber construction methods in areas of primary structure. A high degree of part consolidation must be achieved and primary reliance on mechanical attachment must be avoided. This must be combined with processes capable of high rates of production at a relatively low cost.

2.2 Market Surveys & Feasibility Studies

The ultimate acceptance of electric vehicles is consumer driven, and the performance and price achieved by the electric vehicle must be equivalent to the performance and price desired by the consumer or the vehicle will fail in the market. Two major studies are summarized here.

2.2.1 CARB Results

The California Air Resources Board reviewed several market surveys to determine consumer acceptance of electric vehicles. A market survey conducted by Ford found that 60% of prospective electric vehicle purchasers require a 100 mile useful range[15]. This range is generally not achievable with current vehicular weights and lead acid batteries[16].

2.2.2 NAVC Results

The NAVC conducted studies to predict the future price of electric vehicles[17]. They analyzed three cases; two conversions and one predicted purpose-built EV, which is the same vehicle studied in this thesis. For their analysis, they assumed that the running frame, including chassis, body, interior, bumpers, & other structural components, would initially cost $35,000 and would decrease to $12,000 after production was increased to 20,000 vehicles/year. These estimates were assumed based upon a predicted drop in the price of carbon fibers and a move away from hand molding to volume manufacturing processes. The assumption of a drop in the future price of carbon fiber, however, is currently somewhat in doubt, as the company that was expected to bring out a commodity priced ($5/lb) carbon fiber[18] was purchased by Hercules, an aerospace carbon fiber manufacturer. The price of carbon fiber has since remained relatively steady at $18/lb for large tows[19].

Also assumed in the NAVC study was the use of nickel metal hydride batteries. A preproduction version of these batteries powered a prototype of the composite electric vehicle used in this study to a distance of 238 miles on a single charge[20]. This range is certainly enough to meet most consumers' demands. The batteries are also much more lightweight than a lead acid battery pack, with a weight of 425 lbs compared to weight for a typical lead acid battery pack of around 1000 lbs. The downside to this is the cost; even in volume production these batteries are expected to cost $6000 per set.[21]

With further assumptions of standard cost reductions through volume production in the charger, electric motor, and controller system, the unit cost of a purpose built composite electric vehicle was expected to drop from $60,515 to $22,945, even allowing for the introduction of considerable capital costs ($20 million.[22])

The loss of the possibility of inexpensive carbon fiber from the market may be viewed by some as a removal of hope for a lightweight composite vehicle as several auto manufacturers have attempted to construct commercially viable lightweight vehicle constructed of fiberglass based composites without success. None of the attempts have experienced market success, for reasons detailed above, but this should not be viewed as proof that a lightweight structure cannot be constructed with fiberglass composites.

2.3 Development of Performance, Cost, and Production Level Targets

Several criteria have been set to provide a target for the economic success of the project: weight, production volume, and cost[23]. The weight goal was set at 500 lbs for the complete body structure, including hood, trunk, doors, dashboard, rear seat, and impact structure. The cost target was set at $2500 finished structure, or $5/lb. Production volumes were set at two different levels--a 500/year initial break-even point, and a high volume, 20,000/year full production point. For comparison with steel body-in white platforms, the surface areas and weights of the various components of the body are derived below.

2.3.1 Development of Basis for Body Weight

In order to properly decide how important weight savings are in the parts studied, a first order estimate of the weight and cost of the cosmetic elements of the body must be made. To successfully and accurately model a structure as complex as a car body, a 3D computer model (Figs. 1 & 2) of the surfaces in the vehicle was created in AutoCad. The element of the body that serves a primarily cosmetic purpose is the top shell. The top shell is composed of the following pieces:

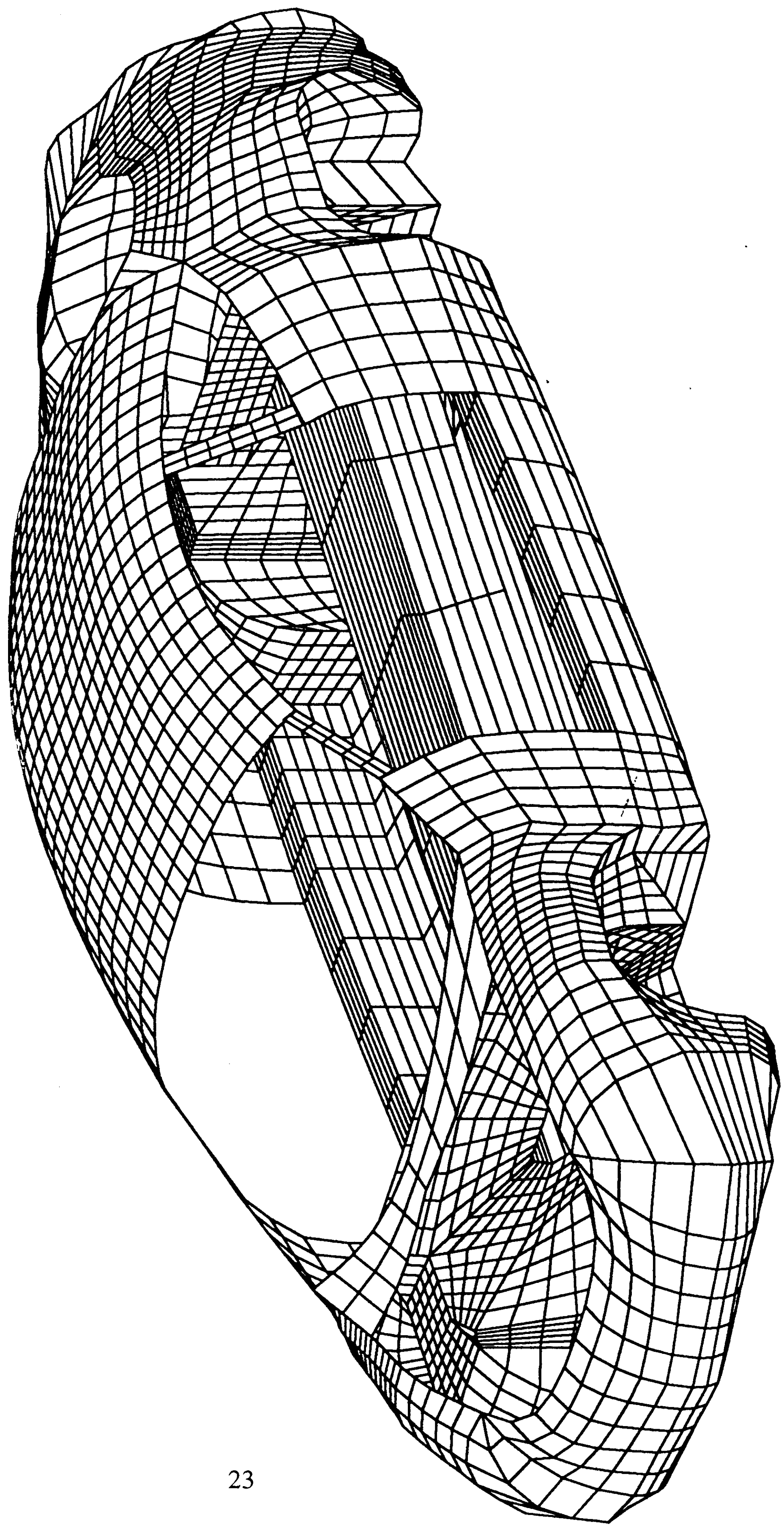
Component name	Area for one side, in^2	Area for two sides, in^2
Roof/Rear Deck	3100	6200
A Pillar	36	72
B Pillar	43	86
Side	832	1664
Rear Quarter	707	1414
Front Quarter	656	1312
Nose	1156	2312
Top Shell	**Total=**	**13060**

Table 2-1. Top Shell Areas

Using a average skin thickness previously demonstrated in composite vehicles of 3.5 mm (.138 in.)[24] we can calculate the volume of the upper body at 1800 in^3. Assuming that internal secondary support structure will add 40% to this, we have a total volume of 2500 in^2 and thus the weight, using a density of .055 lb/in^3 [25], can be estimated at 129 lbs. Based on prototype information, doors weighed 20 lbs/ea., hood/trunk lids 8 lbs/ea., and frontal crash absorption structure 15 lbs, bringing the total to 200 lbs. At a first order finished cost estimate of $5/lb, this gives a finished manufacturing cost of $1000.

This is reasonable as technologies to create composite cosmetic parts are already well established and in use in the automotive area. Examples include the fiberglass shell of the Vette, SMC molding of many hoods and deck lids, SRIM molding of front bumper/fascia assemblies, thermoplastic layered injection molding techniques used by ICI[26], XTC thermoplastic materials used by DuPont, and the Saturn side panels. Thus, the structural components under consideration in this study must collectively weigh less than 300 lbs and cost less than $1500 to produce to meet the cost and weight targets defined earlier.

Figure 2-1. AutoCad Surface Model (Top View)



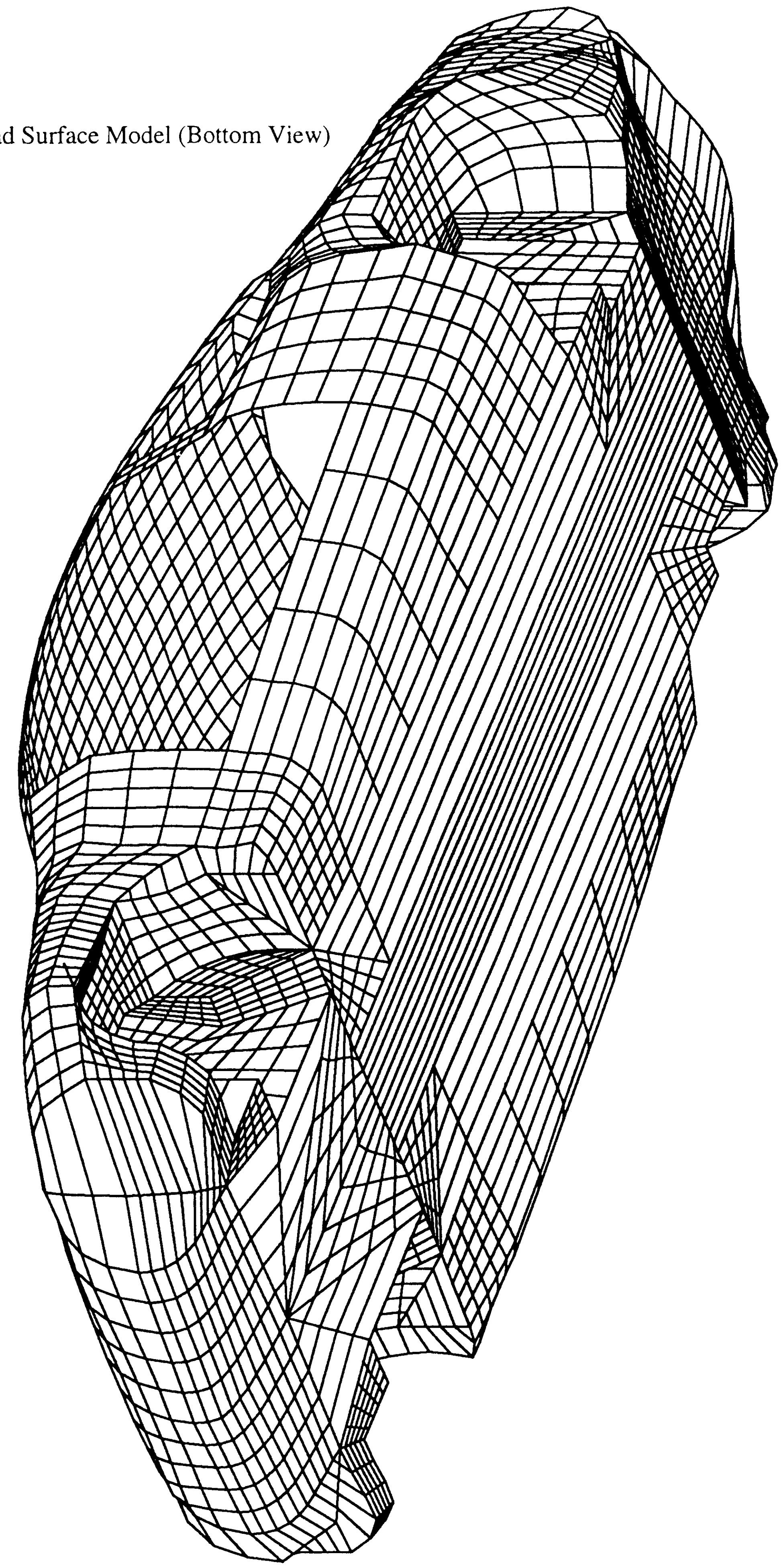


Figure 2-2. AutoCad Surface Model (Bottom View)

For purposes of comparison to existing steel vehicles, the composite goals can also be studied as a 'body in white'. As mentioned previously, this is simply the existing vehicle without 'closure panels'--doors, hood, trunk, front fascia, or front fenders. Using the density and surface area approximations made earlier, the weight and cost goals for a composite body in white are 420 lbs and $2,100. A benchmark average four passenger steel vehicle body-in-white (from the ULSAB study mentioned in Chapter 1) has a weight of 598 lbs and a manufacturing cost of $1,116/vehicle. The proposed ULSAB has a weight of 452 lbs and a manufacturing cost of $962 (both estimated.)

2.3.2 Stiffness and Loading Requirements

Stiffness Targets, derived from averages of steel bodied vehicles[27]:

Beaming (Bending stiffness requirement)=12,200 N/mm=1.436 e-5 in/lb deflection at center of beam

Torsional rigidity=13,000 Nm/deg=8800 ft-lb/deg

Load cases, derived from literature[28]:

3 g vertical bump, front wheels, inertial relief

2g dynamic + 1g static, front wheels

2g dynamic + 1g static, rear wheels

2g panic brake + vehicle dead weight

1g lateral skid + dead weight

Of these, the 3g vertical bump with inertial relief was recognized as the most severe service load[29] and will be the load case used in these preliminary tradeoffs along with the static torsional and bending requirements.

The vehicle has a projected weight of 1800 lbs with 424 lbs of batteries[30], and is designed to take 4 passengers. Assuming a scenario of 4 adults averaging 150 lb each, the gross vehicle weight is estimated as 2400 lbs. This weight was found to be distributed between front and rear wheels in a 50/50 ratio[31], and thus each wheel at one g will carry a load of 600 lbs, generating a maximum impulse load during the 3g vertical acceleration of 1800 lbs at the wheelwell.

Crash loading, as it is a specialized topic, will be discussed separately in Chapter 5.

Chapter 3

Development of Cost and Structural Models

3.1 Cost Modeling-Basic Structure

The basic structure of manufacturing cost modeling can be broken into 5 distinctive groups: Capital, Labor, Tooling, Material, and Energy. Despite being somewhat location dependent in terms of local labor, building, regulation, and other costs, this provides a framework to economically evaluate options.

Capital refers to the machines which produce the parts and their support equipment, Labor refers to the people who operate the machines, Tooling refers to the tools used to provide shape to the material, and Energy is the amount of power required to effect the process. To explain the process, it is easiest to demonstrate the spreadsheet model developed and follow side by side along with it. The examples used will be thermoplastic stamping, thermoset and thermoplastic filament winding, and pultrusion. Resin transfer molding costs were calculated using a proprietary industry model that is not described in depth here but is similar in structure to the others. Raw material cost deserves special mention and thus it is dealt with at the end of the chapter.

3.1.1 Thermoplastic Stamping

Thermoplastic Stamping is a process for creating parts with complex curvature from fibers preimpregnated with thermoplastic resin. The process involves plies being cut with a hardened steel die, stacked on a carrier, and placed into a hot press under pressure, which causes the plastic to melt and the plies to mold together. Then, the plies are quickly transferred to a cold press and cooled under pressure which creates the interlaminar bonds. Finally, the laminate (or ply stack) is transferred to a heating oven, brought to forming temperature, and quickly shuttled into the cold forming press where it is pressed to its final shape and held until solidified. The part is removed, trimmed, and moved to assembly.

The capital cost model is arranged as follows:

Capital		
Annual Production	1000	units
cons. press Tonnage	120	tons
Cons. press cost (2)	584756	$
Length of Production run	6	years
Press Tonnage	120	tons
Press cost	292378	$
Convection Oven Cost	70000	$
Steel Die cutter Cost	$124,000	$
Accounting life of machine	6	yrs
Internal Molding Pressure	200	psi
aux. equip.cost (fract. of mmch)	0.3	%
Installation cost (fract. of mmch)	0.1	%
Overhead cost (fract. of mmch)	0.35	%
Productive Time (fract. of hours)	0.8	
cycle time	2	minutes
# parts possible in year	46080	parts
utilization of machine	0.0217014	
Total capital cost	1290417.5	$
Total capital cost/year	215070	$
Capital cost/ part	215.07	$

Table 3-1. Thermoplastic Stamping Capital Costs

Annual production is the production run required per year; in this case, the simulation is for the 500/year study but requires 1000 parts as the same firewall is used front and rear to gain fuller utilization of the expensive mold. Consolidation press tonnage is the same as the press tonnage of the main press, and the consolidation press cost is simply the cost of 2 additional presses the size of the main press. The Press tonnage is calculated from this simple formula:

$$tonnage = \frac{(part\_area)(processing\_pressure)}{2000}$$

where the processing pressure is 200 psi[32], and the part area for this firewall is 1000 in^2. Press Cost is determined from an study done by Masi[33] and is described by:

$$cost = \$268{,}378 + (\$200)(press\_tonnage)$$

To heat the consolidated laminates to forming temperature just before stamping, a multistage infrared conveyer oven is necessary. The cost of the oven ranges from \$60,000-\$120,000 depending upon the complexity and rate required[34]; \$70,000 was used for this study.

The steel die cutter cost is again based on a study in Masi[35] and is roughly \$124,000. The Accounting Life of the machine is the time period over which the machine is amortized or paid for. Using 6 years is actually somewhat conservative, as a heavy press is actually serviceable for much longer than this time period, but 6 years is an accounting standard.

The Auxiliary Equipment, Installation, and Overhead costs are all estimates to approximate a series of complicated costs encountered in the machine's setup and day to day operations and upkeep. These numbers are derived from a study done by Busch[36] on industrial cost modeling.

Productive Time is a percentage of the available work hours that is actually used for part production and is a conservative average from several studies of factory work. Tool changeover time is incorporated into this estimate.

Cycle Time is the most critical number of the process, for it determines the maximum part production rate and thus the number of parts the capital cost can be conceivably be spread over. This is derived from Quadrax™'s processing guidelines for high performance thermoplastic composites[37] and is set at 2 minutes for the oriented layup components and 1 minute for the randomly oriented components (dashboard, floorpan, and rear seat.) This seems to be somewhat conservative; some thermoplastic material manufacturers have demonstrated cycle times of well under 30 seconds.[38]

Parts Possible describes the quantity of parts that can possibly be produced with respect to cycle time, working hours, and productive time:

$$\#\_parts = \frac{(working\_hours)(productive\_fraction)(60\_\min s / hour)}{cycle\_time}$$

Utilization of Machine describes the fraction of the machine's time that is actually used for this production run:

$$utilization = \left(\frac{annual\_production\_run}{\#\_parts\_possible} \right)$$

Total Capital Cost is the complete cost of the capital equipment.

$$total\_\cos t = \begin{pmatrix} aux\_eq\_\$ + \\ install\_\$ + \\ overhead\_\$ + \\ 1 \end{pmatrix} * main\_\$ + oven\_\$ + die\_\$ + 2(consd\_\$)$$

Capital Cost/Year is the total capital cost divided by the accounting life of the machine, and Capital Cost/Part is the Capital Cost/Year divided by the annual production run.

Labor is simply the cost of the people operating the machines. Labor rates were assumed to be $25/hour, with a workweek comprising 5 days at 8 hours per shift for a total of 1920 hours per year, as shown in the spreadsheet excerpt below. Double shifts, 16 hours/day, were used at higher production volumes when necessary.

Labor		
Direct Wages (w/benefits)	25	$/hour
Working Days/year	240	days
Working hours/day	8	hours
Hours of production time	1920	hours
Direct Laborers/machine	4	
Labor cost/year	192000	$
Labor cost/part	192.00	$

Table 3-2. Thermoplastic Stamping Labor Costs

4 laborers are assumed to work on this machine line, so the labor cost/year and labor cost/part are direct functions of the above conditions and of the production schedule.

Tooling is one of the most costly aspects of preparing for a production run; presses and other general equipment can be used for several different parts, but tooling is part specific.

Tooling		
Tooling	152221	$
Rough cutter die cost	1200	$
# of passes req'd	1	passes
Life of tooling	6	years
Cost/year of tooling	25570	$
Cost/part of tooling	25.57	$

Table 3-3. Thermoplastic Stamping Tooling Costs

Two sided, matched metal tooling is assumed in this case; the equation describing matched tooling cost as a function of area is[39]:

$[0.22*454*part\_weight+.423*projected\_part\_area*2.54^2+339]*20/tool\_material\_factor$

The tool material cost factor mentioned above is 0.5 for P20 steel and 2.35 for aluminum. P20 steel is assumed for all calculations in this study.

The cutter die cost was studied by Masi[40] and is modeled by:

*die_cost=$1000+$19*perimeter/12*

The life of the steel tooling used for composite forming is quite high and it is unlikely th... proposed production volumes of composite electric vehicles will be sufficient to wear out steel tools; however, the accounting life of the tool provides an accurate assessment of the distributed cost of the tool as the vehicle will be updated at least every six years. The cost/year of tooling is simply the initial cost divided by the accounting life, and the tooling cost/part is the cost/year divided by the annual production run.

It must be noted here that some studies have encountered difficulty in forming thermoplastic composite parts with matched metal tooling; the rapid cooling of the composite caused by contact with the cold metal causes loss of formability and subsequent tearing or fiber distortion[41]. For this reason, the male half of the tool is typically a metal form over which has been cast a silicone block to match the female tool. This provides even consolidation at lower cost but does not provide the same two sided tooled surface accuracy of steel tooling, which is useful to avoid tolerance buildup in the complex joining surfaces of road vehicles. For this reason, a composite tool comprised mainly of an elastomer punch but with matched metal surfaces where necessary for joining operations is assumed in use where necessary; it is also assumed that this will have a cost similar to that of a matched metal tool.

As mentioned previously, material cost is simply the weight of the component multiplied by the cost/lb of the material in question. Scrappage is ignored in this study due to difficulty of prediction; it is recognized that this is not a trivial cost in composite manufacturing due to the high cost of the material and further study is indicated in this area. It is assumed every effort to minimize waste will be made, including recycling of waste material into non primary structure components such as cosmetic panels and interior supports.

Material	
Prepreg cost/lb	$2.25 dollars
Prepreg thickness/ply	0.0078 in
Density	0.07 lb/in^3
Part area	1000 in^2
Projected area	950 in^2
Max. thickness	0.125 in
average thickness	0.125 in
Part weight	8.75 lbs
# plies	16
Rough perimeter	126 in
Material cost/part	19.69 $

Table 3-4. Thermoplastic Stamping Material Costs

Energy cost in this case is assumed to be largely due to the operation of the preheating oven; as this is further assumed to be a 200A, 440V rms oven, the power consumption is found to be (200A)(440V)=88 kW. The number of kilowatt-hours of energy used in a year is simply the operational hours times the power consumption; in this case (1920 hours/year)(88 kW)=169 MWh/year. Cost of energy varies with location but is assumed to be $0.08/kWh for a total of $13520/year. This cost is multiplied by the utilization of the machine and divided by the number of parts produced to gain energy cost/part figures.

Drawing these various components together, we can find the overall cost of the component:

Costs	
Capital cost/ part	215.07 $
Labor cost/part	192.00 $
Tooling cost/part	25.57 $
Material cost/part	19.69 $
Energy cost/part	13.52 $
Total cost/part	452.94 $
Cost/lb	$51.76 $
Costs (utilization base)	
Capital cost/ part	4.67 $
Labor cost/part	4.17 $
Tooling cost/part	25.57 $
Material cost/part	19.69 $
Energy cost/part	0.27 $
Total cost/part	54.10 $
Cost/lb	6.20 $
Percent capacity used	2.17 %

Table 3-5. Thermoplastic Stamping Total Costs

The costs at top are simply the previously mentioned costs added up; as you will notice, this produces an extremely expensive part for small production runs. For a more realistic assessment of the actual cost of the part, we will assume that, at volumes low enough that a single part's production utilizes only a tiny fraction of the available machine capacity (2.2% in the example above), several parts would be made from the same production line, using the capacity more thoroughly, and the capital, labor, and energy costs would be changed to reflect this distributed use. This is called utilization based cost. In this case, nearly 50 similar parts would need to be run from the same line; this is a difficult task considering the degree of parts consolidation expected in the vehicle. This difficulty is reflected in the conclusions in Chapter 4 on process selection.

Material cost is unaffected by this change, for the same amount of material is used per part no matter what the production run, and likewise tooling is not affected because one tool cannot be used for any other purpose but to make the part it was designed for. Thus, for utilization based cost, the capital, labor, and energy costs are multiplied by the utilization of the machine that particular run actually uses, providing greatly reduced costs.

A word of caution must be spoken here; the lowered costs shown in the utilization based figures can only be realized if the machine is indeed fully utilized; thus the dies and the material feed line have to be rapidly reset for each new component. This is the centerpiece of the lean production system developed in Japanese automobile manufacturing plants. For accurate cost analysis, the actual utilization of the machine must be measured in practice and results derived from that.

3.1.2 Filament Winding

For Filament Winding (thermoset and thermoplastic), the model is much the same as the thermoplastic stamping model with the exception of the Capital and Tooling costs, which are studied here. This model is based on a study by Busch[42] but in a more simplified form.

Capital	
Annual Production	500 units
Length of Production run	6 years
Machine cost	50000 $
Curing oven size	125 ft^2
Curing Oven Cost	176620.25 $
Curing oven usage allowed	0.3
Curing oven usage	0.30
Accounting life of machine	6 yrs
aux. equip.cost (%mmch)	0.3 %
Installation cost (%mmch)	0.1 %
Overhead Burden (%mmch)	0.35 %
Productive Time (fraction of available labor time)	0.8
Mat. dep. rate	1.25 lbs/min
Cycle time	77.1 min
# parts possible in year	1194.7
utilization of machine	0.4185
Total capital cost	264120.25 $
Total capital cost/year	44020.01 $
Capital cost/ part	88.04 $

Table 3-6. Filament Winding Capital Costs

This model was calculated using the 500 units/year benchmark. Machine cost was set at $50,000 each, with a material deposition rate of 1.25 lbs/min[43]. This allows the cycle time to be derived according to the following equation:

$$cycle\_time = \frac{part\_weight}{deposition\_rate}$$

The number of machines needed for a given production goal can be calculated as follows:

$$\#\_machines = \frac{annual\_production}{production / machine}$$

using methods similar to those used in the thermoplastic stamping model.

Oven size follows as a direct consequence: the curing time of the materials used is about 3 hours[44] and so the number of parts cured in 3 hours must match the number of parts wound in 3 hours. As the cycle time for the part in question is 51 minutes, 4 parts must be cured simultaneously to match the rate. Each part is 9 cubic feet in volume, and limiting the usage of the oven to 30% of its volume capacity to allow adequate airflow[45] necessitates an oven of sufficient size:

$$oven\_size = \frac{(part\_volume)(\#\_cured)}{volume\_utilization}$$

Oven cost is calculated according to an equation derived by Masi[46].

$$oven\_cost = \$12,129 + (\$1315.93)(oven\_volume, ft^3)$$

Mandrel changeover time is incorporated into the Productive Time fraction. Total capital costs and annual/part capital costs are calculated similarly to the thermoplastic stamping model.

Tooling costs consist of the mandrels required for production.

Tooling		
Mandrel cost/ea.	3000.00	$
# mandrels	9	
cost of mandrels	13587.24	$
cost mandrels/year	2264.54	
tooling cost/part	0.11	

Table 3-7. Filament Winding Tooling Costs

The mandrel cost for the battery box is $3000[47], and the number of mandrels required is twice the number that are curing in the oven at any given time (one set of mandrels is continuously being wound while the other set is curing.)

$$\#\_mandrels = \left(\frac{180\_\text{min.}}{cycle\_time}\right) x2$$

Total mandrel cost, cost of mandrels/year and tooling costs/part are all straightforward. Labor is calculated similarly to the thermoplastic stamping model except that only one operator on average is assumed. Similarly, the cost of energy based on oven use is calculated similarly to that of thermoplastic stamping. The mandrels are assumed to be collapsible, thereby removing the need for expensive hydraulic puller equipment to separate the cured part from the mandrel.

Thermoplastic filament winding is calculated similarly to thermoset filament winding except that the material deposition rate is lower (0.62 lbs/min[48]), there is no oven used for curing, and there are only two mandrels required as the part can be removed from one while the other is being wound. The base machine cost increases by $5,000 due to the addition of a gas torch[49] to heat the material as it is deposited on the mandrel. Also, energy cost is assumed negligible due to the lack of an oven in continuous operation.

3.1.3 Pultrusion

Pultrusion receives special attention as it is known to be one of the lowest cost methods of producing composite parts due to rapid processing and its highly automated nature. The pultrusion cost model is set up similarly to the others, with capital, labor, tooling, materials, and energy cost.

Capital		
Annual Production	20000	units
Length of Production run	6	years
Machine cost	120000	$
Accounting life of machine	6	yrs
aux. equip.cost (%mmch)	0.3	%
Installation cost (%mmch)	0.1	%
Overhead (%mmch)	0.35	%
Productive Time (%avail.time)	0.8	%
rate	3	ft/min
Cycle time	2.92	min
# parts possible in year	39497	
utilization of machine	0.51	
Total capital cost	210000	$
Total capital cost/year	35000	$
Capital cost/ part	1.75	$

Table 3-8. Pultrusion Capital Costs

The 20,000/year production case is demonstrated. Main machine cost is set at $120,000[50] and obtains a production rate of 3 ft/min[51]. Cycle time is thus calculated as:

$$cycle\_time = \frac{part\_length}{pultrusion\_rate}$$

Capital costs are then calculated similarly to previous models.

Tooling for pultrusion is typically chrome plated steel to withstand the high pressures and temperatures of the pultrusion process. Pultrusion die cost for this application is estimated at $150,000[52]. Tooling cost/part is calculated similarly to previous models.

Labor for pultrusion also assumes an average of only one person working on the machine, as the process is highly automated. Labor cost/part calculations are otherwise identical to those previously studied. Energy costs are assumed negligible as the only component heated is a relatively small die kept at constant temperature.

3.1.4 Resin Transfer Molding (RTM)

Resin Transfer Molding is a process by which a dry fiber preform is die cut, stamped into shape, and placed into a matched mold. The mold is then placed into a press to provide sufficient pressure for high volume fraction results and evacuated to remove any air remaining. Resin is then 'transferred' into the mold from outside tanks, typically through a mixing nozzle. The mold is heated and cooled to cure the resin.

The resin transfer molding cost model used for this application is a proprietary industry model of a structure similar to the previously mentioned cost models. Identical costs are assumed for the matched metal toolsets for RTM and thermoplastic stamping. Resin transfer molding is a relatively slow process, with cycle times generally around 30 minutes required for high volume fraction, high performance component manufacturing, which is the cycle time assumed for these cost calculations. Thus, the process is not capable of spreading out the cost of a matched tool set over a large number of parts to the degree that thermoplastic stamping is. However, this is somewhat offset by the lower cost of the raw materials, as mentioned previously, and the lower capitalization costs; production capable resin transfer molding machines are available at prices as low as $25,000[53]. Press costs can be calculated using the same equations used as those for thermoplastic stamping presses.

3.1.5 Other Composite Manufacturing Processes

There are many other automated composite manufacturing processes that were not included in the cost/performance tradeoffs as they lack high volume fraction capability. Structural Reaction Injection Molding is a high speed method of composite part manufacturing in which a preform is placed into a high pressure mold and a two part resin is injected into the mold at a very high rate of speed and pressure. This process produces low cycle times, on the order of 5 minutes, but is generally not capable of over 35-40% volume fraction. This process is effective, however, for items such as suspension links that are not bending or torsional stiffness driven and are more typically sized for external impact or damage tolerance.

Vacuum based, single sided tool processes, using a flexible elastomer diaphragm or disposable bag, are popular due to their low capital cost. Vacuum based resin transfer type molding systems without a source of extra pressure on the diaphragm side are typically not consistently capable of over 40% volume fraction in a manufacturing environment, however, which removes these systems from consideration. Likewise, vacuum assisted forming for thermoplastic materials is a popular and inexpensive method, and the preimpregnation of the thermoplastic fibers at the prepregging facility removes the difficulty of achieving high volume fractions. This process has limitations, however, in the thickness of laminate that can be successively thermoformed; this limit is typically about 0.080" thick[54] and is thus not sufficient for the thicker laminates used in the construction of this composite vehicle.

3.2 Materials Cost

Materials cost is one of the most fundamental obstacles to the widespread adoption of composite materials in automotive applications. As such, it requires close examination.

One of the primary choices to be made in the arena of composites is whether to use a thermoset or a thermoplastic resin. The thermoset resins are more familiar and have a wider base of use, while the thermoplastic resins offer the promise of lower manufacturing costs and recyclability, and their prices are continually decreasing. It is impossible at the outset to say with certainty which is the better choice, and so this study will look at both families to determine their relative strengths and weaknesses.

Within the thermoplastic and thermoset families, there are several levels of cost and performance. There are commonly available families of long fiber random oriented 'mat' products oriented at the automotive body panel market which provide relatively low mechanical properties but offer rapid processing cycles and low cost (for example, volume pricing for XTC is $1.50/lb at 50,000 lbs/year, achievable at the 500/year volume production level, to $1.35/lb at 250,00 lbs/year, achievable at the 20,000/year production level.)[55]

These are represented by the following commercial product names:

Material		Modulus
GE:	Azdel (random)	0.9[56] Msi
	Azdel (directionalized)	1.4 (Parallel) 0.7 (Transverse) Msi
	Azmet (random)	1.2 Msi
	Azloy (random)	1.1 Msi
DuPont: XTC		1.1[57] Msi
SMC-R40		1.9 Msi

Table 3-9. Low Performance Composite Materials

These materials do not have sufficient performance to be used in primary automotive structure; their stiffnesses and strengths are resin dominated and thus they are relegated to primarily cosmetic components.

Thermoset materials exist in commodity form as glass unidirectional fibers wound on creels or woven into cloth and raw resins. Polyester resins are the least expensive ($1.23/lb typical) and have the least desirable properties in strength, creep, shrinkage, and impact resistance. Vinylester resins are more expensive (typically $1.70/lb) and have slightly improved properties over polyester. Epoxy resins are the highest cost ($5+/lb) and the highest performance. Polyester resin was chosen for this application as the improved properties of vinylester and epoxy were not judged sufficiently high to overcome the increase in price. However, for some highly loaded components such as composite leaf springs, epoxy resins are typically used as their creep resistance is superior to that of the vinylesters and polyesters.

There are also an increasing number of high performance thermoplastic composites on the market which have high mechanical properties by virtue of their unidirectional or woven construction and high volume fractions of glass fiber. The most common low cost resins currently used and studied include PPS (polyphenylene sulphide), PEI (polyether imide), PP (polypropylene), PET (polyethylene terapthalate) and variations of nylon. Thermoplastic matrix composite materials are not yet in widespread use; however, some work has been done to characterize these materials for creep properties[58], and basic stiffness and strength properties are available from manufacturers' product information.

A word should be said about creep properties of thermoplastic composites, as these are expected to be inferior to thermoset composites. Available literature has indicated that creep is not evident in fiber dominated directions but is evident in matrix dominated directions. One example of matrix dominated creep would be tensile or compressive forces on a [±45] laminate instead of shear forces. Every effort has been made in this study to ensure that the laminates are loaded only in the directions dominated by fiber, as this is the method that uses the properties of the fibers to the greatest effect.

Thermoplastic materials are currently relatively expensive materials in the prepreg form ($4/lb-$15/lb) but as the raw material costs of the combined constituent materials and resins are low[59] and the processing steps are straightforward[60] their cost should steadily decrease toward the levels demonstrated on the following chart. The cost of prepregging is a cost that is estimated, for high production volume thermoplastic prepregging, to come down to $1/lb[61]. This is not unprecedented; impregnation costs in SMC are typically $0.25/lb-$0.35/lb, although the process is not controlled as closely. The entire material cost for DuPont XTC PET/E glass, including prepregging, is around $1.40/lb as mentioned previously. $1.25/lb costs are assumed to allow for materials supplier profit margins. Vinylester/E glass and polyester/E glass are included in the chart for reference to common thermoset prices. 'sg' in the chart refers to 'specific gravity' of the material indicated; this is the material's density with respect to pure water, which has a sg of 1.

PP/E glass		
vol% fiber	55	
weight % fiber	77.66	
PP sg	0.9	
glass sg	2.56	
prepreg cost	1.25	$/lb
cost PP	0.5	$/lb
cost glass	1.04	$/lb
cost composite	2.17	$/lb

Nylon/E glass		
vol% fiber	55	
weight % fiber	73.64	
Nylon sg	1.12	
glass sg	2.56	
prepreg cost	1.25	$/lb
cost Nylon	1.5	$/lb
cost glass	1.04	$/lb
cost composite	2.41	$/lb

PET/E glass		
vol% fiber	55	
weight % fiber	69.86	
PET sg	1.35	
glass sg	2.56	
prepreg cost	1.25	$/lb
cost PET	0.9	$/lb
cost glass	1.04	$/lb
cost composite	2.25	$/lb

PEI/E glass		
vol% fiber	55	
weight % fiber	69.70	
PEI sg	1.36	
glass sg	2.56	
prepreg cost	1.25	$/lb
cost PEI	6.21	$/lb
cost glass	1.04	$/lb
cost composite	3.86	$/lb

Vinylester/E glass		
vol% fiber	55	
weight % fiber	71.95	
vinylester sg	1.22	
glass sg	2.56	
cost vinylest.	1.82	$/lb
cost glass	1.25	$/lb
cost composite	1.41	$/lb

Polyester/ E glass		
vol% fiber	55	
weight % fiber	70.65	
polyester sg	1.3	
glass sg	2.56	
cost polyester	1.23	$/lb
cost glass	1.25	$/lb
cost composite	1.24	$/lb

Nylon/carbon		
vol% fiber	55	
weight % fiber	66.27	
Nylon sg	1.12	
carbon sg	1.8	
prepreg cost	1.25	$/lb
cost Nylon	1.5	$/lb
cost carbon	18	$/lb
cost composite	13.68	$/lb

Table 3-10. Composite Raw Material Prices

The main tradeoffs in selection of thermoplastic resins are cost, impact resistance, chemical resistance, processability, and service temperature[62]. PPS has excellent resistance to most solvents, and, in a toughened form, has high impact resistance . Its glass transition temperature, and thus its service temperature, is relatively low-only 83°C, which could cause problems in hot environments. Fundamentally, however, its chief detriment is its high price/lb, which will be seen to dominate thermoplastic manufacture and force the choice of polymer.

Nylon derivatives are chemical resistant and posses high glass transition temperatures (280°C) but are hydroscopic and absorb water, in some cases up to 5% by weight. This typically causes a severe decrease in compressive strength properties when it is fully saturated (30% loss after immersion for 5 days.)[63] However, they offer good performance through their strong adhesion to fibers and consequently are used in several sporting goods applications, such as the GT LTS-1 carbon fiber bicycle frame and the SPIN Composites injection molded carbon fiber/nylon tri- spoked bicycle wheel. Current prepreg costs at high volumes are $4/lb.

PEI in its raw resin form is expensive at $6.21/lb. The composite material cost is estimated at $3.35/lb. PEI offers a high glass transition temperature (240°C), ease of processing, and very high toughness. The chemical resistance of PEI was once a problem, but recent resins from GE Plastics/Cyanamid Co. such as Cypac X7005 have been formulated to address this problem. However, commercial PEI/composites are typically oriented toward graphite fibers due to the high cost.

PP composites have the benefit of being very inexpensive. PP/E glass is produced commercially for $3.50-$4.00/lb[64], which can be expected to decrease under high volume production runs. However, they are severely limited by their temperature range and are not considered applicable for primary structure applications that will see the high temperatures experienced by automotive applications.

Polycarbonate materials are attacked by ultraviolet light and by aromatic hydrocarbons such as gasoline and are thus impractical for extensive use in automotive environments.

For automotive purposes, the extreme low cost of PET composites, combined with fair strength performance and excellent resistance to chemicals, impact, and temperature seem to be the most favorable combination. The environmental resistance and service performance of these composites have also been indicated by industry experts[65] to be superior to the nylon and PP based composites, and a large, low cost supply of the polymer material exists as regrind from recycled soft drink containers. This material is being developed commercially and is expected to be available for $2.25/lb in quantities of 10,000 lbs/year or more.[66]

3.3 Structural Analysis of Composites

Composite materials are inherently more complicated to analyze due to their orthotropic nature. Thus, a hybrid combination of analytic solutions, classical laminate plate theory, and finite element analysis is employed to accurately predict the performance of these materials under the conditions encountered in vehicular use.

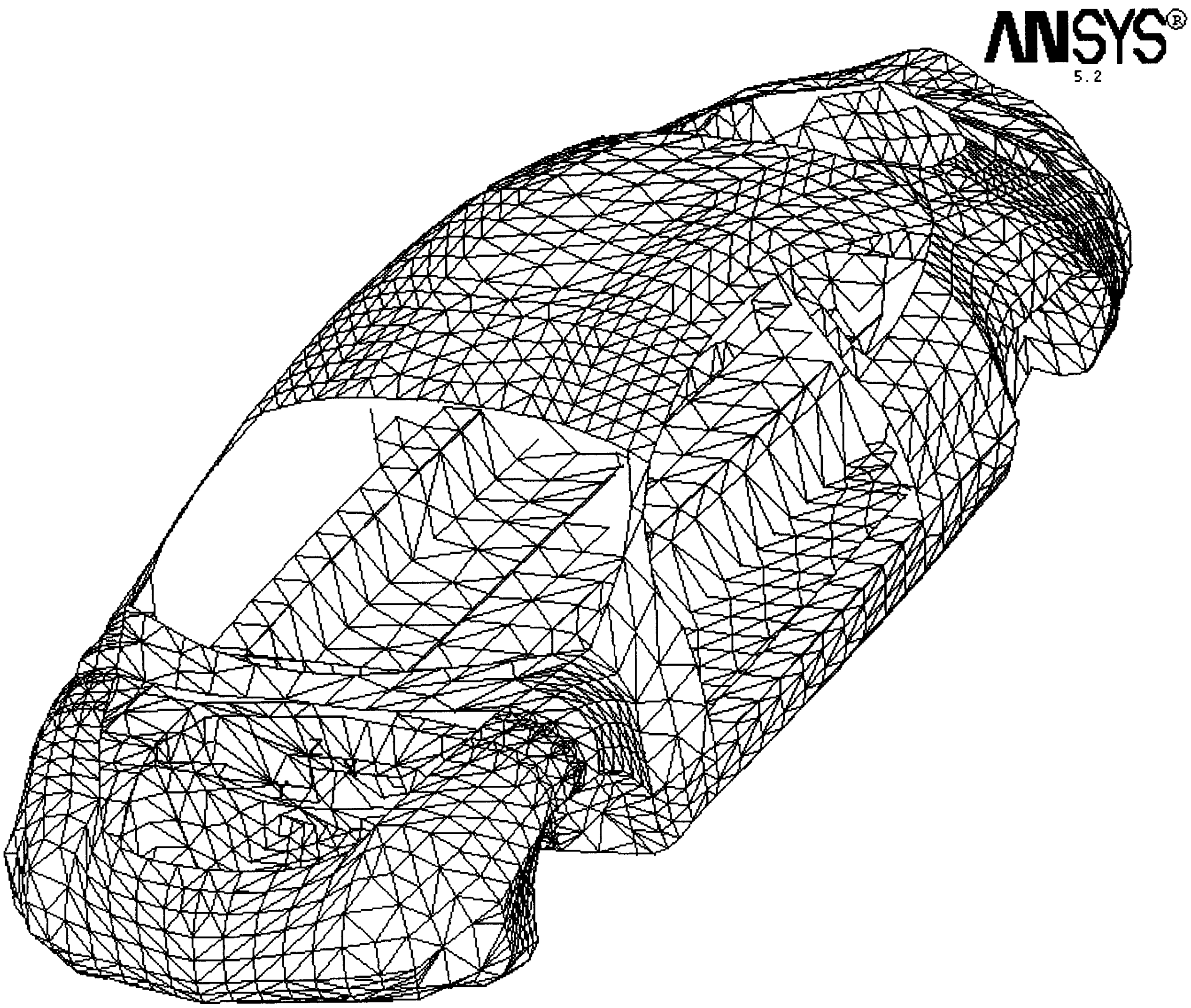
Classical Laminated Plate Theory is a standard method of mathematically analyzing laminated orthotropic plates, and is explained extensively elsewhere[67]. In this study, it is used primarily to determine average mechanical properties of various layups for use in analytic solutions for bending, torsion, and deflection. These can be rapidly iterated using a spreadsheet to converge on an optimum use of the material. The computer code used to calculate the material constants is contained in the Appendix.

Finite element analysis is used both in the preliminary analysis of the vehicle to determine load paths and in the detailed design of the wheelwell, to determine proper composite layup. Combined with CLPT, it can provide 'usage factors' of individual plies in a section of the structure that indicate when failure will occur for a given loading. Thus, a finite element model (fig. 3-1) was constructed to assist in the analysis of the vehicle structure. It incorporates 6782 triangular three node elements and 3347 nodes.

Figure 3-1.

Vehicle Finite

Element Model



3.4 Composite Performance Data

As mentioned previously, the thermoset materials chosen for this study for their performance and cost are E glass in the 24 oz. woven roving and unidirectional forms with polyester resin. 24 oz. woven roving is available in large quantities (over 2500 lbs) at $1.25/lb, and polyester resin is available at $1.23/lb in quantities over 1000 lbs[68]. These quantities are achieved even at very low production levels.

The key performance data required for design with composites are the elastic modulus parallel to the fiber direction, Ex; the modulus across the fiber direction, Ey; the in plane shear modulus, Gxy; Poisson's ratio parallel to the fiber direction, nu/x; the density of the material, and the cost/lb of the material. Composite performance data for the E glass roving/polyester composite at 55% volume fraction (achievable using matched metal molds and hydraulic presses, both of which are assumed in the cost modeling) are[69]:

Ex:	3.0 Msi
Ey:	3.0 Msi
Gxy:	0.6 Msi
nu/x:	.11
Density:	.062 lb/in^3
Cost:	$1.24/lb

Unidirectional E glass is available as chopper gun roving creels at $1.04/lb in quantities over 2,500 lbs[70]. In the unidirectional form, the E glass/polyester composite properties at 55% volume fraction are[71]:

Ex:	6.2 Msi
Ey:	1.2 Msi

Density and cost are assumed similar to the roving material.

As mentioned above, the thermoplastic material chosen for this study is E glass in the unidirectional form and PET resin, which is projected to be commercially available at \$2.25/lb. Composite material properties for this at 55% volume fractions are[72]:

Ex:	6.8 Msi
Ey:	2.0 Msi
Gxy:	0.8 Msi
nu/x:	.29
Density:	0.068 lb/in^3
Cost:	\$2.25/lb

Thermoplastic nylon 6/carbon is an increasingly popular material in use in sporting goods; although its expense is too high to be used extensively in the structure, it nonetheless has potential for a high degree of weight savings if used selectively. It has substantially improved stiffness properties over E glass based composites as is demonstrated by the material properties.

Ex:	16.0 Msi
Ey:	1.1 Msi
Gxy:	0.74 Msi
nu/x:	0.28

For the components that can be filament wound, the following properties are used, based on E-Glass/Epoxy[73] (polyester based material properties unavailable):

Fiber volume: 50%

Density: 0.067 lb/in^3

Wind Angle (0 deg is parallel to rotational axis)=15

Ex: 4.62 Msi

Ey: 1.60 Msi

Gxy: 0.60 Msi

nu/x: 0.491

Wind Angle=45

Ex: 0.94 Msi

Ey: 0.94 Msi

Gxy: 1.60 Msi

nu/x: 0.780

For Pultruded components, the unidirectional material values used are[74]:

Ex: 6.2 Msi

Density and material cost are similar to the E glass/polyester material previously mentioned.

Polyurethane foam is a popular inexpensive core material used for making sandwich panels. In this case it is used as core in the firewalls. The foam used in this study is General Plastics Polyurethane Last-A-Foam with the following properties[75]:

Density: 12 lb/ft^3

Comp. Strength: 550 psi

Shear Modulus: 4.5 ksi

Cost: $6/lb

These materials will be analyzed in the following analyses to determine the optimal combination of materials and processing techniques.

Chapter 4

Component Structural/Cost Development

4.1 Choice of Components

In order to make the analysis and cost/performance tradeoffs a more manageable task, only the main structural components of the vehicle were considered. These include:

Floorpan

Wheelwells

Front and Rear Firewalls

Battery Box/Center Tunnel

Rocker Boxes

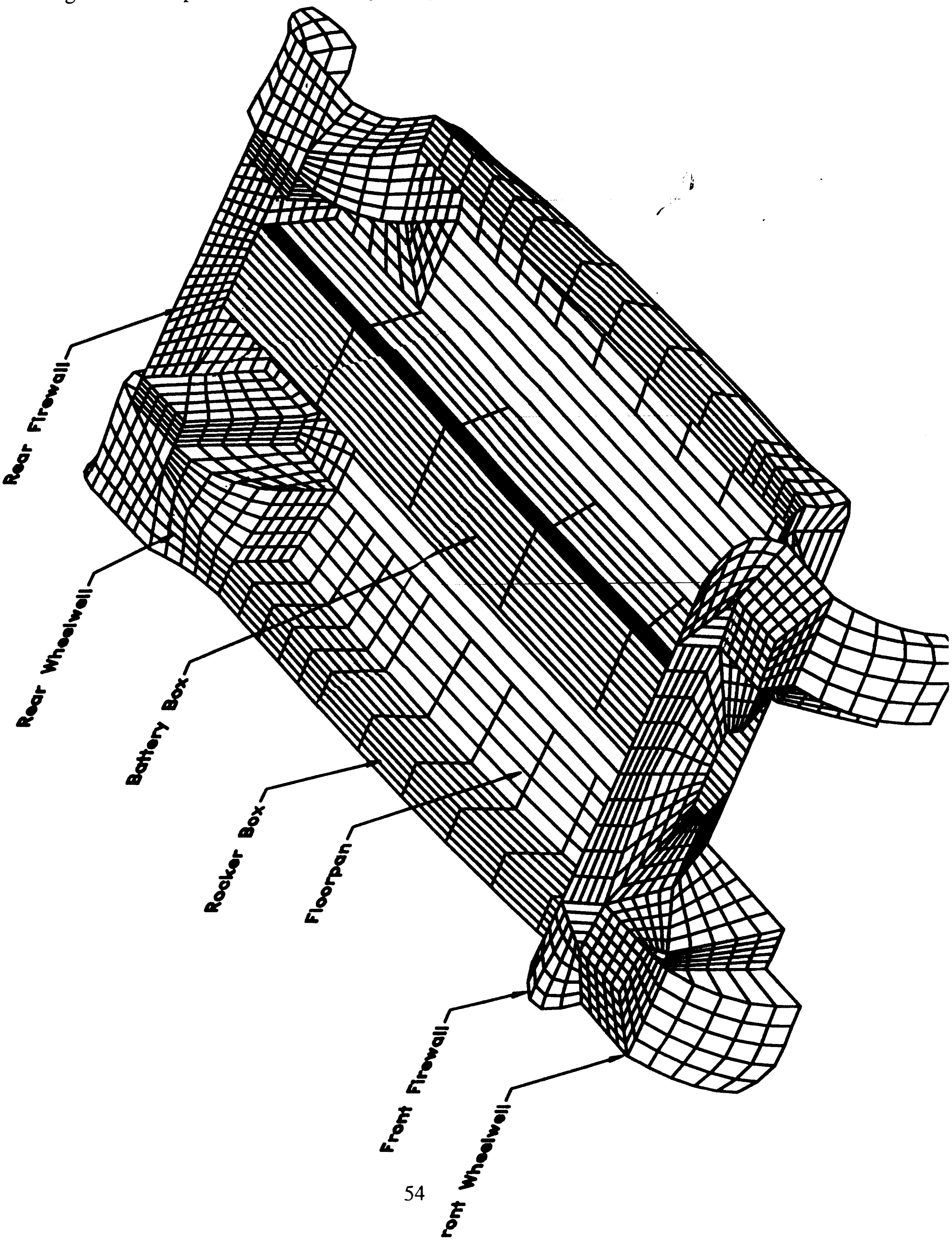
Dashboard

Rear Seat

Crash Absorption Structure

These components are shown in figure 4-1. From initial tests with the finite element model of the entire vehicle it was found that these particular components had a primary role in defining the structural performance of the vehicle. The roof and door pillars of the vehicle also contribute a small amount of torsional and bending rigidity, but their function is primarily for side impact and rollover protection which is not covered in this study. Most of the remainder of the structure of the vehicle can be described as primarily cosmetic. The energy absorbing crash structure has requirements that differ markedly from the rest of the components so it will be covered separately in Chapter 5.

Figure 4-1. Exploded View of Study Components



These components were chosen as they represent logical breakpoints in the continuum from discrete stampings, such as those used in steel cars, to completely integrated 'clamshell' structures, such as those used in the Lotus Vacuum Assisted Resin Injection process. These components, while providing a moderate level of parts integration, are still readily manufactured by most modern composite processes. Higher levels of part consolidation are estimated to cause difficulty with molding. Problems with full resin infiltration with resin transfer molding begin to occur as the part size increases to very large levels, and integration of the battery box with any other component would tend to preclude the use of filament winding.

Other part consolidation options were examined as well, however, and the results of these inquiries are included.

4.1.1 Top/Bottom Shells

Lotus vehicles use a process they term VARI, for Vacuum Assist Resin Injection. They are able to mold their bodies in 2 large moldings by this method[76]. The method is essentially resin transfer molding using large epoxy dies clamped together by vacuum pressure, achieving impressive parts consolidation and component reduction. Essentially, the entire primary structure examined in this study could be made in a one piece resin transfer molding.

However, resin transfer molded components that are not consolidated under pressure beyond that supplied by vacuum through presses or autoclave pressure are typically unable to achieve the high volume fractions necessary for successful primary structure. This limitation can be seen in Lotus cars by their use of a steel backbone chassis for all primary structure applications, with the fiberglass body structure only used for secondary structure and cosmetic functions. A mold capable of molding an entire vehicle top or bottom with the requisite 100-200 psi to achieve high compaction would necessarily be a very large structure; a rough estimate based on this electric vehicle is 163 in. x 72 in.

=11,736 in^2 which requires a press capable of 600-1200 tons, at a cost of $256,000-$505,000, using similar press costs as were used for thermoplastic stamping. This is not insurmountable, as presses this size are commercially available; NC machining a matched molding die nearly 14 feet long to tolerances sufficiently high to control the volume fraction would however be costly. The amount of hand layup that would be required to successfully place the required reinforcements in the necessary locations would also be excessive; the coarsely woven materials used for automotive applications due to cost limitations do not 'drape' well and are not suited for extremely complex curvatures.

Another problem in this approach is yield: in very large resin transfer molded structural parts, the presence of defects or air bubbles causes an unacceptably high scrap rate that is difficult to combat because of the extremely complex nature of the flow front and the unpredictability of the infiltration from one part to the next.

4.1.2 1 pc. Pultruded Floorpan

A 1 piece floorpan, with integrally molded rocker boxes and battery box manufactured through the pultrusion process was also considered. However, the extremely high scrap rates that would result from having to cut out large sections of the pultrusion to fit the wheelwells in cause this to be an unattractive proposition, as the thermoset material cannot be recycled easily. The rocker boxes are 80 in. long while the center tunnel is 105 in. long, creating 50 in. of waste pultrusion for each vehicle made.

4.1.3 TP Roll Forming

Thermoplastic rolling is a process where a preconsolidated continuous sheet of thermoplastic laminate is passed successively through multiple sets of heated rollers, each set bending the laminate closer to its final shape. This allows for the continuous manufacture of sections, which would be analogous to thermoset pultrusion and would offer large labor savings because of its automation and simplicity. The concept is demonstrated in fig. 4-2. However, as has been demonstrated previously, the cost of thermoplastic parts is already dominated by their higher material costs and so the minimal savings in labor would be offset by the relatively larger material scrap rates caused by the removal of large amounts of material to provide the openings for the wheelwells. The thermoplastic scrap material can be recycled into body panel material, but as it is more expensive to make high performance unidirectional material than randomly oriented body panel material ($2.25/lb vs. $1.40/lb) the loss is significant. With further improvements in high performance low cost material manufacturing this may become a viable option.

4.1.4 Consolidation of Firewalls/Wheelwells

One part consolidation possibility that has a high potential is the consolidation of the firewalls and the wheelwells. When split along the line where the firewall intersects the wheelwell, the structure would be readily produced by a stamping operation. This of course produces a seam relatively close to the highly load shock absorber/spring mounting point, but the force direction would cause the bond to be loaded in almost pure shear, which is the best way to load adhesive bonds[77]. This concept is demonstrated in fig. 4-3. The risk of loading a joint so heavily was determined to be excessive for this initial study, but further work here is warranted.

Figure 4-2. Thermoplastic Roll Forming Concept

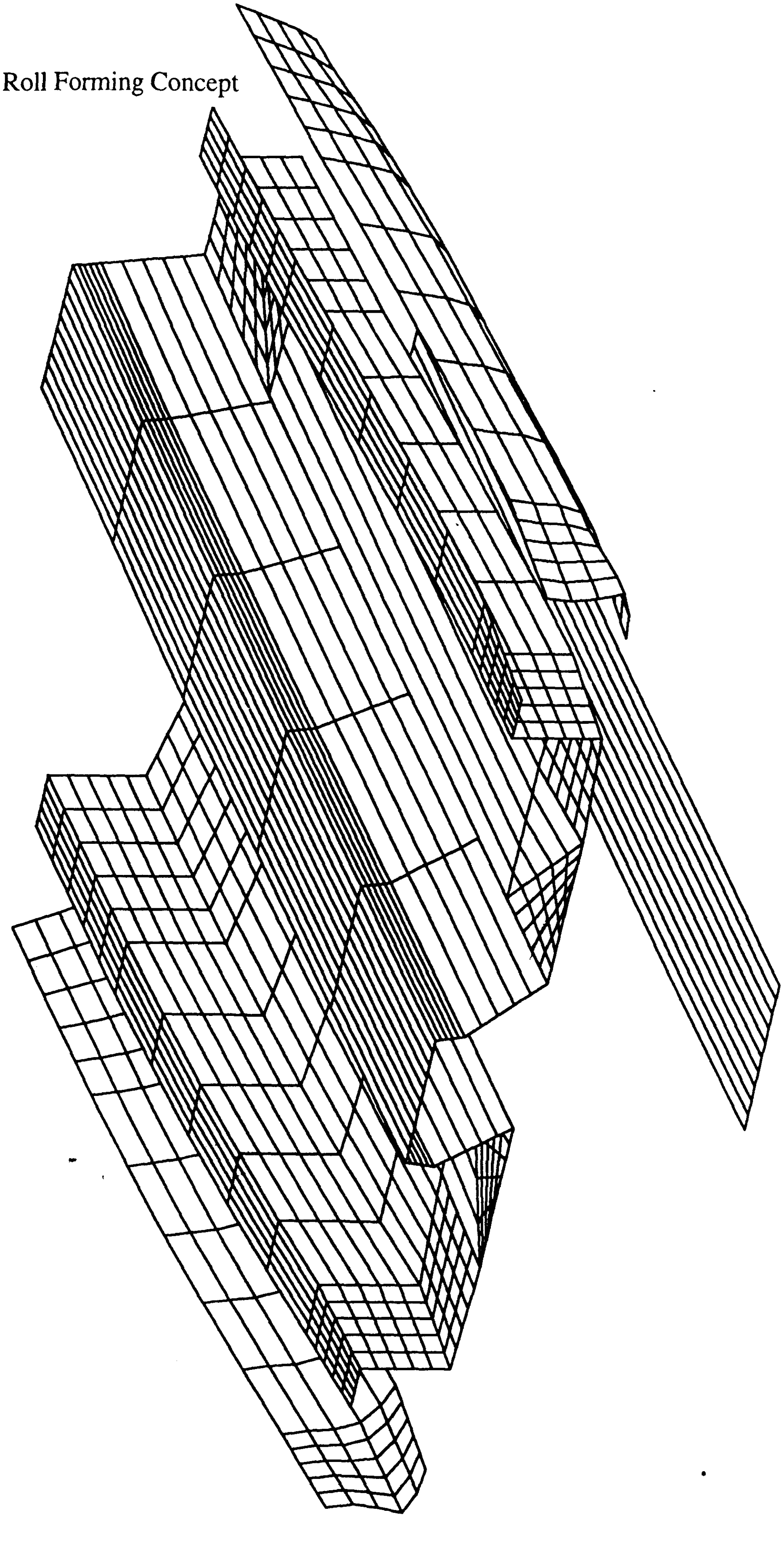
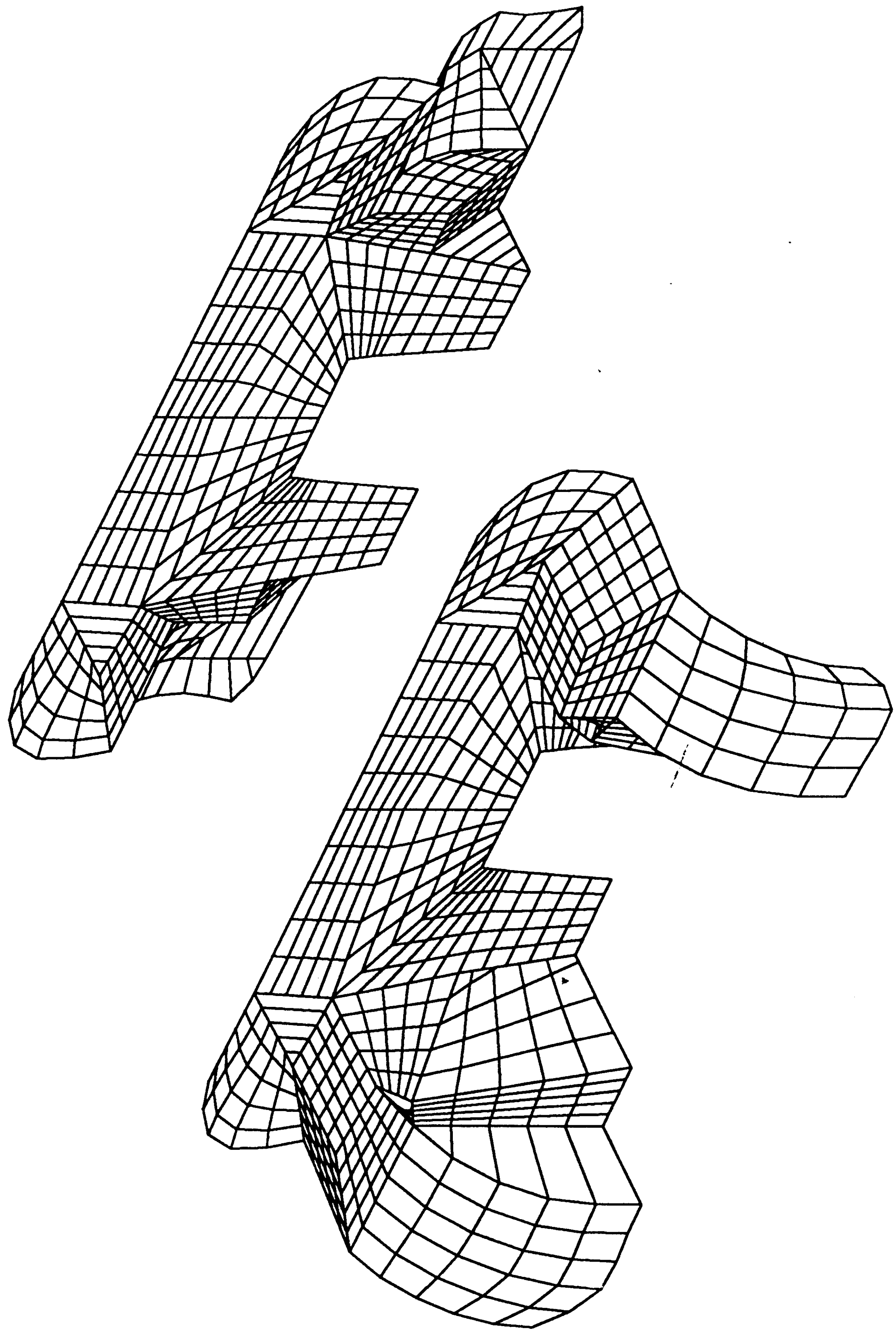
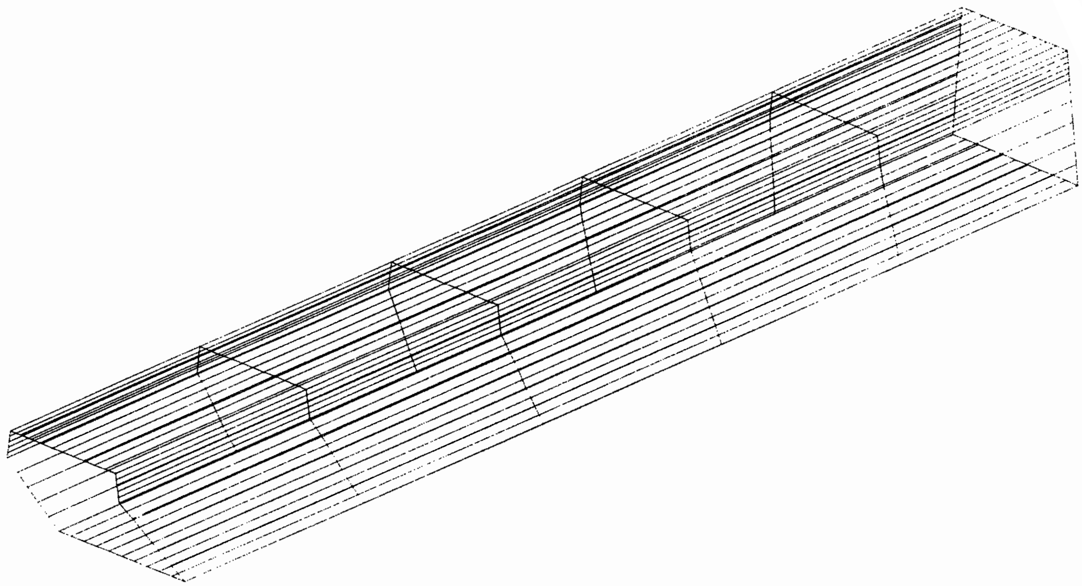


Figure 4-3. Firewall/Wheelwell Consolidation Concept



4.2 Battery Box



Dimensions: 12x12x105"

Area: 5040 in^2

4.2.1 Requirements

The battery box is the main load carrying member in the vehicle structure. To determine the degree to which the vehicle structure relies on the battery box, a finite element analysis of the full body structure was performed to calculate the torsional load carried by the roof structure. The roof structure was modeled as 2"x2", 0.125 in. thick quasisotropic E glass square section A, B, and C pillars combined with the existing outer skin. This demonstrated that the torsional loads from the suspension points depend almost completely upon the battery box structure; the roof structure, including A, B, and C pillars, contributed very little (less than 200 ft -lbs/degree) to the torsional rigidity. The rocker boxes contribute to bending rigidity as they can be well coupled to the shock towers and to the center of the tunnel via seat supports, but they were not found to contribute substantial rsional stiffness to the structure as the wheelwells flexed and prevented a torsional load pa from being completed.

The rocker boxes are mentioned here because their bending rigidity is factored into the calculations for the required thickness and layups of the battery box. As indicated by their use in primarily bending loads, the rocker boxes were assumed to have a unidirectional layup, 0.125" thick. This thickness was chosen to provide sufficient thickness to withstand the weight of a passenger stepping upon the rocker box during entry or egress. This results in a weight for 2 boxes of 24.4 lbs. Thus, for calculation purposes it is assumed that the specifications for torsional rigidity will take into account only the battery box, and the calculations for bending rigidity will take into account the main battery box and the rocker boxes.

4.2.2 Manufacturing Processes Examined

The stiffness requirements for the battery box/rocker box combination, as stated previously, are:

Beaming (bending): 1.44 e-5 in/lb (deflection of the center of the beam in 3 point bending under a 1 lb load)

Torsional rigidity: 8800 lb/deg

Various manufacturing techniques are evaluated to determine their suitability to meet stiffness requirements at the least possible weight and cost.

RTM

For RTM using ply layups a somewhat involved design process is required. Using classical laminated plate theory (given in Appendix), various ply combinations were attempted using an iterative spreadsheet method to determine the least amount of material needed to meet the bending/twisting stiffness requirements.

Batt. Box			
	base	12	in
	height	12	in
	thickness	0.23	in
	Iyy	325.63	in4
	Itorsional	500.22	in4
	area	10.83	in2
	thickns 0s	0.1	in
	weight box	91.67	lbs

Rockr. Box			
	radius	6	in
	thickness	0.125	in
	Iyy	108.51	in4
	Itorsional	39.83	in4
	area	2.31	in2
	length	80	in
	E1 (psi)	6.20E+06	psi
	weight boxes	24.36	lbs

technique	E1(psi)	G (psi)	bnd. stfn.	trsnl. rgd.	density	weight
RTM	3.16E+06	1.34E+06	1.42E-05	9280	0.066	91.7

Table 4-1. RTM Battery Box Stiffness

Based upon the properties of woven roving and unidirectional E glass/polyester resin previously given, a 0.23 in. layup consisting of 6 layers of 0.038 in. thick 24 oz. woven roving at 45^{o} was chosen for the main skin of the battery box. At the top and bottom of the battery box, this layup was supplemented with 0.1 in. thicknesses of unidirectional E glass fibers as in bending this is the area where unidirectional fibers are most effective. The weight of the battery box using this layup is 91.7 lbs.

Filament Winding

The primary method of changing mechanical properties in filament winding comes from varying the winding angle. Using a similar spreadsheet method to that used above in the RTM design and material properties with respect to wind angle data[78], the wind angle was varied iteratively until the stiffness requirements in the bending and torsional cases were evenly matched, with no wasted excess stiffness in either case. The minimum thickness required was 0.29 in, generating a part weight of 96.5 lbs. The slight gain in weight over RTM resulted because filament winding does not allow the deposition of extra unidirectional plies on the top and bottom of the component, as was used in the RTM process. Part weight, properties, and wind angles were assumed similar for the thermoplastic filament winding process.

technique	E1(psi)	G (psi)	bnd. stfn.	trsnl. rgd.	density	weight
wind@25	3.17E+06	1.05E+06	1.46E-05	9031.29	0.066	96.5
wind@20	3.96E+06	8.20E+05	1.27E-05	7053	0.066	96.5
wind@24.5	3.25E+06	1.03E+06	1.43E-05	8833.46	0.066	96.5

Table 4-2. Filament Wound Battery Box Stiffness

TP Stamping

A similar construction to that of RTM is assumed for the thermoplastic stamping of the battery box. As it is obviously difficult to stamp a closed section (the 'box' shaped battery box) it is assumed that the box is stamped in two separate sections, later to be electromagetically welded together to complete the tubular structure.

An approach similar to that used for the RTM layup was used to determine the necessary thickness and layup for the thermoplastic material, with performance differences resulting largely from the use of unidirectional plies instead of woven cloth, which allows more efficient torsional usage of the material and less weight (the weaving and subsequent bending of the fibers in cloth results in suboptimum fiber properties). The resulting lack of bending and thus performance improvement of the fibers is significant in reducing the weight of the box.

Iteration resulted in a $[\pm 45]_{10}$, 0.156 in. thick laminate for the main torsional structure of the box, with 0.1 in. thick unidirectional reinforcement (13 layers) in the top and bottom of the box. Box weight is 70.0 lbs.

technique	E1(psi)	G (psi)	bnd. stfn.	trsnl. rgd.	density	weight
TP stamp	4.10E+06	2.00E+06	1.42E-05	9570.85	0.068	70.0

Table 4-3. Thermoplastic Stamped Battery Box Stiffness

Pultrusion

Pultrusion is often considered to be a process primarily suited for unidirectional reinforcement, but successful high fiber volume, multiaxially reinforced pultrusions have been demonstrated[79]. A $[0/\pm45]_n$ laminate was studied for this application, with material properties generated with CLPT analysis. As the pultrusion process is dependent on unidirectional plies to successfully pull the material through the die, the possibility for weight reduction used in thermoplastic stamping and RTM by using only ±45 plies on the vertical sides of the battery tunnel is not practicable here. The required thickness is 0.29 in, and the weight of the part is 94.1 lbs.

The multilayer, multiangle layup is assumed to be achieved through the use of angular overwinders to produce the ±45 plies interspersed with the 0 degree plies; this approach allows the use of inexpensive unidirectional glass loaded on creels. The required layup and volume fractions were indicated by pultrusion application engineers to be achievable with this technique[80]. Stitched cloth fiber was considered and rejected due to its high costs ($1.70/lb even at high volumes)[81].

technique	E1(psi)	G (psi)	bnd. stfn.	trsnl. rgd.	density	weight
pultrude	3.30E+06	1.10E+06	1.42E-05	9461.35	0.066	94.1

Table 4-4. Pultruded Battery Box Stiffness

4.2.3 Manufacturing Results

RTM/TP stamping matched tool cost: $430100

Manufacturing Costs: 500/year

	RTM	Fil. Wd.	Pult.	TP stamp	TP Fil. Wd.
Capital cost/ part	$15.78	$36.85	$0.89	$5.98	$27.91
Labor cost/part	$24.93	$40.18	$2.43	$4.17	$83.51
Tooling cost/part	$163.37	$4.00	$50.00	$147.81	$2.00
Material cost/part	$138.51	$115.71	$112.86	$157.74	$223.69
Energy cost/part	$7.65	$11.31	$0.00	$0.29	$0.00
Total cost/part	$350.24	$208.05	$166.18	$315.99	$337.11
cost/lb	$3.82	$2.16	$1.77	$4.51	$3.39
% molding used	16.40	41.85	1.27	1.09	86.99
% preforming used	1.12				
Part weight (lbs)	91.70	96.50	94.1	70	96.5

Manufacturing Costs: 20,000/year

	RTM	Fil. Wd.	Pult.	TP stamp	TP Fil. Wd.
Capital cost/ part	$15.78	$7.63	$0.89	$5.98	$0.82
Labor cost/part	$24.93	$40.18	$1.22	$4.17	$83.51
Tooling cost/part	$25.59	$0.12	$1.25	$3.70	$0.00
Material cost/part	$138.51	$115.71	$112.86	$157.74	$223.69
Energy cost/part	$5.26	$1.26	$0.00	$0.29	$0.00
Total cost/part	$210.07	$164.89	$116.21	$171.88	$308.02
cost/lb	$2.29	$1.71	$1.24	$2.45	$3.10
% molding used	93.69	93.00	50.64	43.40	96.66
% preforming used	44.74				
Part weight (lbs)	91.70	96.5	94.1	70	96.5

Table 4-5. Battery Box Manufacturing Costs

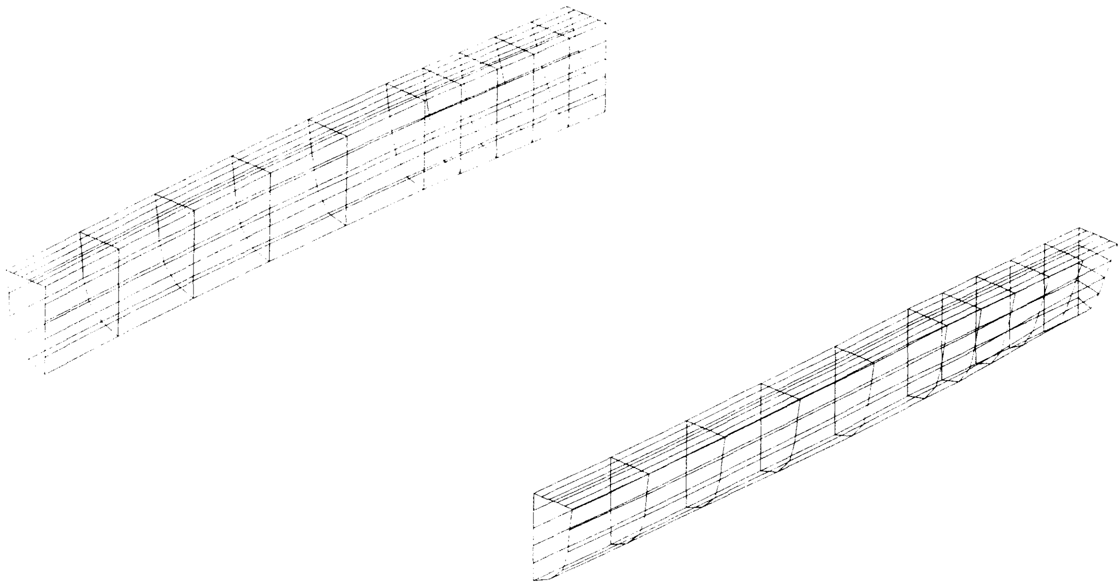
To meet the production rate of 20,000/year, the RTM, filament winding, and TP filament winding processes all required multiple machines and double shifts, which account for their high % of utilization. The TP stamping and pultrusion processes required only one machine and one shift to meet production goals.

4.2.4 Conclusions

As can be seen from the above graphs, some processes are much more economically feasible than others. Pultrusion creates the least expensive product of all, and is the clear winner among thermoset processes. RTM has a slight weight advantage, but as can be seen, 500 units/year already use up 16% of the molding capacity, allowing little room for further growth and suggesting that the process will not improve much with higher volume, as can be seen by comparison of the RTM costs between 500/year and 20,000/year. Thermoset filament winding is inexpensive, largely due to low capital and tooling costs, but is relatively slow, requiring a large number of machines to produce high volumes.

Thermoplastic filament winding is very expensive, as both the labor and materials costs are high due to the deposition rate that is half that of thermoset filament winding. Thermoplastic stamping at high volumes is cost competitive with thermoset processes (except for pultrusion), even with higher material costs factored in. The unsurpassed speed of the thermoplastic stamping operation allows for very high production volumes, with the possibility of using one press for several different parts-only 43% of the capacity was used for the battery box, even at high volumes, suggesting that five different parts could be stamped from one central press with interchangeable dies. However, if production volumes are low, the full cost of the expensive presses and dies will be felt instead of the utilization based costs shown above.

4.3 Rocker Boxes



Area/ea.: 2026 in^2

4.3.1 Performance Requirements

As mentioned previously, the performance requirements of the rocker boxes are met by a unidirectional construction 0.125 in. thick.

4.3.2 Manufacturing Processes Examined

The unidirectional nature of the rocker box construction essentially prevents filament winding from being used, as filament winding becomes less and less productive the closer the winding axis is to zero. This problem was not encountered in the construction of the battery box as its loading was a combination of bending and twisting; this allowed a 24.5 degree wind angle to provide an optimum tradeoff between bending and torsional performance. As the rocker box is assumed to be loaded primarily in bending, its optimum fiber orientation is 0 degrees. Accordingly, the processes studied were RTM, TP stamping, and pultrusion.

4.3.3 Manufacturing Results

RTM/TP stamping matched tool cost: $179381

Manufacturing Costs: 1000/year (2/car)

	RTM	TP Stamp	Pult.
Capital cost/ part	$15.78	$5.00	$0.68
Labor cost/part	$24.93	$4.17	$1.86
Tooling cost/part	$39.90	$30.67	$25.00
Material cost/part	$16.42	$31.91	$14.65
Energy cost/part	$6.20	$0.29	$0.00
Total cost/part	$103.23	$72.04	$42.19
cost/lb	8.46	$5.08	$3.46
% Molding cap. used	32.79	2.17	1.94
% Preform cap. used	2.24		
Part weight (lbs)	12.20	12.2	12.2

Manufacturing Costs: 40,000/year (2/car)

	RTM	TP Stamp	Pult.
Capital cost/ part	$15.78	$5.00	$0.68
Labor cost/part	$24.93	$4.17	$0.93
Tooling cost/part	$10.71	$0.77	$0.63
Material cost/part	$16.45	$31.91	$14.65
Energy cost/part	$5.26	$0.29	$0.00
Total cost/part	$73.14	$42.14	$16.89
cost/lb	6.00	$2.97	$1.38
% Molding cap. used	93.69	86.81	77.55
% Preform cap. used	89.47		
Part weight (lbs)	12.20	12.2	12.2

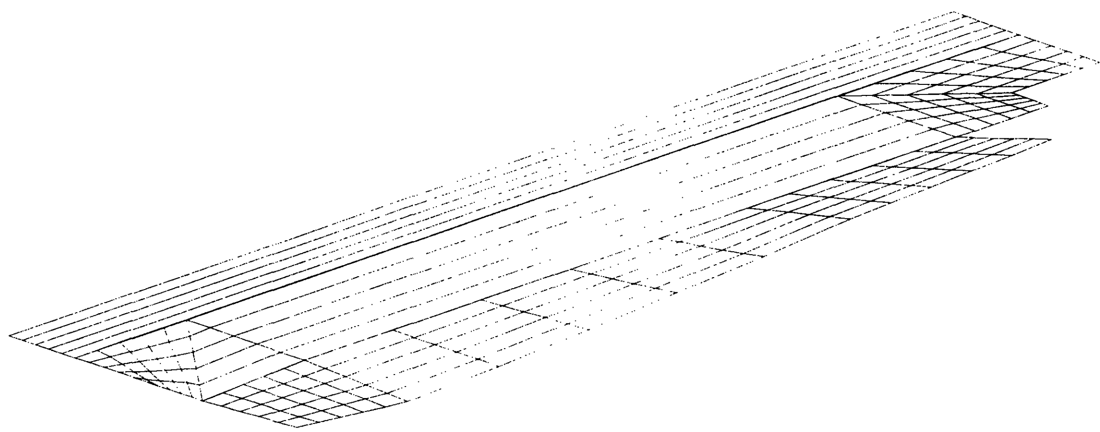
Table 4-6. Rocker Box Manufacturing Costs

4.3.4 Conclusions

Pultrusion clearly is ideally suited for this application. At an identical part weight to the RTM process, it generates a unit cost of 1/4 that of RTM. The thermoplastic stamping process has high productivity and low capital/labor costs similar to the pultrusion process, but has higher material costs compared to pultrusion due to the higher material cost/lb of the thermoplastic material.

It must again be remembered in studying the results that they are based on percentage capacity used--in the case of 1000/year, only 2% of the molding capacity is used. Even if the excess molding capacity is partially used in the production of other components, it will be difficult to fully utilize the capacity of the press in a production run of only 500. It may be possible if the entire outer body as well as the structural component is stamped from a thermoplastic material such as XTC. In the 40,000/year case, pultrusion and thermoplastic stamping use a high (nearly 78%-87%) percent of the machine's time and thus it can be seen that these processes require high rates of production to take full advantage of their potential.

4.4 Floorpan



Area: 7712 in^2

4.4.1 Performance Requirements

The floorpan does not support any primary loads; twisting and bending are controlled by the rocker boxes and the battery box, and seats are mounted to stringers that connect the rocker boxes to the battery box under the seat mounting points. The floor must support the secondary weight of the feet resting on it, as well as the occasional point loads of occupants standing on it and various secondary support loadings for the primary structure elements of the vehicle.

4.4.2 Manufacturing Processes Examined

RTM

Previous work on composite floorpans[82] [83]indicated that the requirements for the floorpan could be met by a 0.10 in. thick E glass/polyester randomly oriented composite. As the proposed application for this vehicle requires less surface detail and material curvature, the woven roving material and resin used in the remainder of the vehicle can be substituted using a 2 layer, [45/0] quasisotropic layup, providing a 0.10 in. thick laminate with improved properties over the randomly oriented material previously used to allow flow in the SMC operation.

In the previous work in composite floorpans, accurate surface detail was required on both sides and so the component used SMC molding techniques with expensive matched metal molds. As application and joining requirements for the current vehicle allow the material to only be tooled on one side, and the relatively low performance required allows the use of vacuum bagged RTM instead of matched metal molds, considerable savings in mold costs can be realized and these are incorporated into the model. At high volume fractions, the 2 layer laminate under consideration would yield only a 0.078 in. thick laminate, but as vacuum based resin infiltration systems have difficulty achieving over 40% volume fraction, the two layers are each assumed to generate 0.050 in. of thickness.

Thermoplastic Stamping

The thermoplastic stamping was based on XTC randomly oriented PET/E glass composite, 0.100 in. thick, which will closely duplicate the properties of the SMC molding material. Matched metal molds are required for the thermoplastic stamping process and thus this high cost is reflected in the tooling costs per part for the low volume manufacturing case below. The lower structural requirements for this component also allow the use of a rapid 1 minute cycle time, which is incorporated into the model.

4.4.3 Manufacturing Results

TP stamping matched tooling cost: $1064925

RTM single sided tooling cost: $532463

Manufacturing costs: 500/year

	RTM	TP Stamp
Capital cost/ part	$15.78	$3.43
Labor cost/part	$24.93	$2.08
Tooling cost/part	$197.49	$357.69
Material cost/part	$72.42	$73.42
Energy cost/part	$7.65	$0.15
Total cost/part	$318.26	$436.76
cost/lb	$6.52	$8.33
% Molding cap. used	16.40	0.54
% Preform cap. used	1.12	
Part weight (lbs)	48.80	52.4

Manufacturing costs: 20,000/year:

	RTM	TP Stamp
Capital cost/ part	$15.78	$3.43
Labor cost/part	$24.93	$2.08
Tooling cost/part	$31.56	$8.94
Material cost/part	$72.42	$70.80
Energy cost/part	$5.26	$0.15
Total cost/part	$149.95	$85.39
cost/lb	$2.77	$1.63
% Molding cap. used	93.69	21.70
% Preform cap. used	44.74	
Part weight (lbs)	48.80	52.4

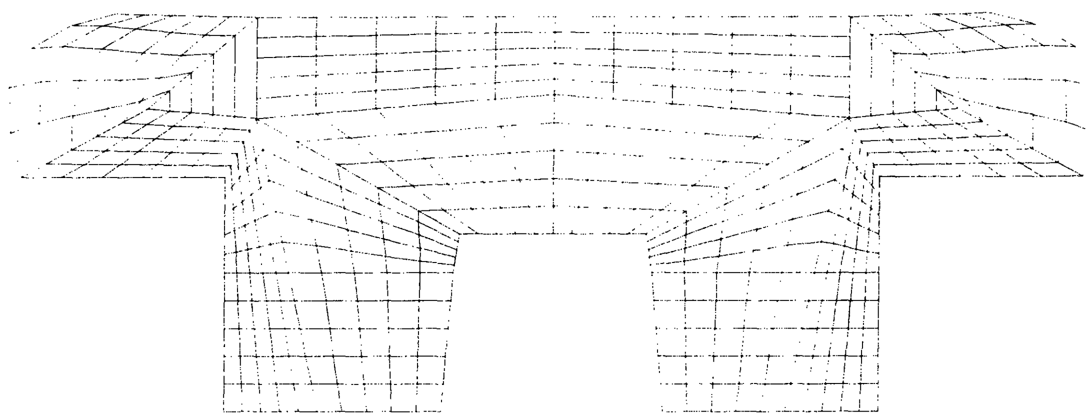
Table 4-7. Floorpan Manufacturing Costs

4.4.4 Conclusions

As is expected, the thermoplastic stamping in this relatively large part is initially more expensive than resin transfer molding the part, largely because of the expensive die and the higher cost of material. However, at high volumes, the higher productivity of the TP stamping process surpasses the RTM process and is preferable.

A further note should be made. In this case, the extreme size of the component drives the equation used to predict tooling to very high prices. The extremely high prices of the floorpan in the 500/year projections are due to the amortization of an expensive tool over very few pieces. In reality, initial production tooling would probably be constructed of a series of steel profiles cut to shape with a steel sheet fitted to the profiles. This is possible as the panel is single curvature in the current vehicle model.

4.5 Firewalls



Area: 998 in^2

The firewalls' original purpose is illustrated by their name; to prevent engine fires from extending into the passenger area. This has little importance in an electric vehicle. However, the firewalls still must transfer the torsional loads from the wheelwells and strut towers to the battery box, which provides most of the torsional rigidity of the vehicle.

4.5.1 Performance Requirements

The critical performance requirements of the firewall is to successfully transfer the forces from the wheelwell to the battery box without buckling. From finite element analysis of the structure it was determined that only the bottom 12 inches of the firewall defined the load path from the wheelwell to the battery box. Using a standardized design methodology[84], it is possible to determine the necessary thicknesses of skin and core.

4.5.2 Manufacturing Processes Studied

RTM

Using a layup of 1 layer of 24 oz. woven roving oriented at ± 45 degrees generates a skin thickness of .038 in. The loading of 1800 lbs is assumed to be distributed evenly over a length of 12 in., giving a shear line load N_s of 150 lb/in. This information was entered into the CLPT code mentioned earlier and used to determine laminate material properties and skin stresses in the plies.

Laminate Material Properties

Ex:	1.8 Msi
Ey:	1.8 Msi
Gxy:	1.3 Msi
nult:	.48

Ply	Stress (X)	Stress (Y)	Stress (Shear)
45	1.970 ksi	-1.970 ksi	0.00 ksi

The maximum allowable stress in the plies is 20 ksi (the fatigue endurance limit)[85] and so it is apparent that the laminate will not fail by tensile, compressive, or shear stress.

Now, the core thickness to avoid buckling must be calculated. This is performed according to the sequence of steps detailed in MIL Handbook 23A, Structural Sandwich Composites. The following variables are known:

N_s:	150 lb/in
b/a:	0.67
lambda=1-nu^2:	0.77
(lambda)($F_{s1,2}$)/$E_{1,2}$:	0.000844
(E_2t_2)/(E_1t_1):	1

With this information the charts are consulted using the initial approximation V=0 and it is determined that h/b=0.01 and thus skin centroid distance h=.12 and thus the chart indicates that, at the theoretical minimum case, core thickness t_c=0.82 for the initial approximation.

With this initial approximation, we can calculate the value of V, originally assumed to be 0, to derive a more accurate thickness of core required due to the non infinite shear stiffness of the core material.

$$V = \frac{\pi^2 t_c E_1 t}{2\lambda b^2 G_c}$$

where t_c is the core thickness, E_1 is the modulus of elasticity of the laminate, t is the skin thickness, lambda and b are as defined previously, and G_c is the core shear modulus associated with the axes parallel to panel side of length a and perpendicular to the plane of the panel. For 12 lb/ft^3 polyurethane foam, the shear modulus is 4.5 ksi[86]. V can then be calculated as 0.06.

This value of V is then used to consult the chart set again; with the result that the actual required h/b=0.01, so h=0.12. t_c is then found to be 0.082 in, which is not a standard manufactured thickness of PU foam. 0.25 in. thick PU foam, a thickness that is readily available commercially, is used. This results in a conservative design, but the excess foam adds very little weight or cost: the two 12"x18"x0.25" PU foam sheets, one for each side of the structure, add 0.75 lbs to the weight and $4.50 to the cost of the firewall. The total weight for the firewall is then 6.2 lbs.

The standard methodology also assumes that the buckling values calculated are for a panel with four sides fixed; this is a key assumption and having only 3 sides fixed will seriously degrade the buckling performance of the sandwich structure. The buckling calculations also assume that the line force generated by the shock tower is a straight vertical force generating pure shear, when in fact the force vector is identical to the stroke path of the strut, tilting somewhat away from vertical.

Both of these issues can be addressed by adding in a strip of unidirectional material that bridges from the firewall to the battery box, serving simultaneously as a load path for the nonvertical forces in the shock tower and as a fourth side to the shear panel (the other three sides are composed of the battery box wall, the floorpan, and the shock tower side.) Using a strip 1 in. wide and 0.25 in. thick, identical to the core thickness used above, stresses in the strip under a maximum estimated off axis load are:

(1800 lbs)(sin 15 deg)/(1 in.)(.125 in.)=1.9 ksi

which is well below the 80 ksi (est.) compressive stress endurance limit for the unidirectional material. It is assumed the strip will be prevented from Eulerian buckling by the presence of the structural front dash panel after it is bonded in.

Thermoplastic Stamping

As it is somewhat more difficult to utilize inexpensive core materials using thermoplastic materials, for issues due to cost and manufacturability, in this case some weight gain will be compromised in order to gain rapid stampability. Using a 0.125 in. thick laminate with [±45] layup, CLPT derived material properties and stresses are:

Ex:	2.44 Msi
Ey:	2.44 Msi
Gxy:	2.0 Msi
nult:	0.522

Ply	Stress (X)	Stress (Y)	Stress (Shear)
+45	2.0 ksi	-2.0 ksi	0.00
-45	-2.0 ksi	2.0 ksi	0.00

As was previously done, the following variables are calculated:

N_s:	150 lb/in
b/a:	0.67
lambda=1-nu^2:	0.73
(lambda)($F_{s1,2}$)/$E_{1,2}$:	0.000596
(E_2t_2)/(E_1t_1):	1

Following similar procedures to those above, the initial h/b is found to be 0.01 and h=0.12 in. t_c from this is then found to be zero and thus the initial assumption that V=0 is correct and no core is necessary to support the load without buckling. Part weight is somewhat greater (8.75 lbs) but manufacturability is greatly improved.

4.5.3 Manufacturing Results

RTM/TP stamping matched tool cost: $152221

Manufacturing costs: 1000/year

	RTM	TP Stamp
Capital cost/ part	$15.78	$4.67
Labor cost/part	$24.93	$4.17
Tooling cost/part	$35.37	$25.57
Material cost/part	$8.29	$19.69
Energy cost/part	$6.20	$0.29
Total cost/part	$95.07	$54.39
cost/lb	$15.33	$6.22
% Molding cap. used	32.79	2.17
% Preform cap. used	2.24	
Part weight (lbs)	6.20	8.75

Manufacturing costs: 40,000/year

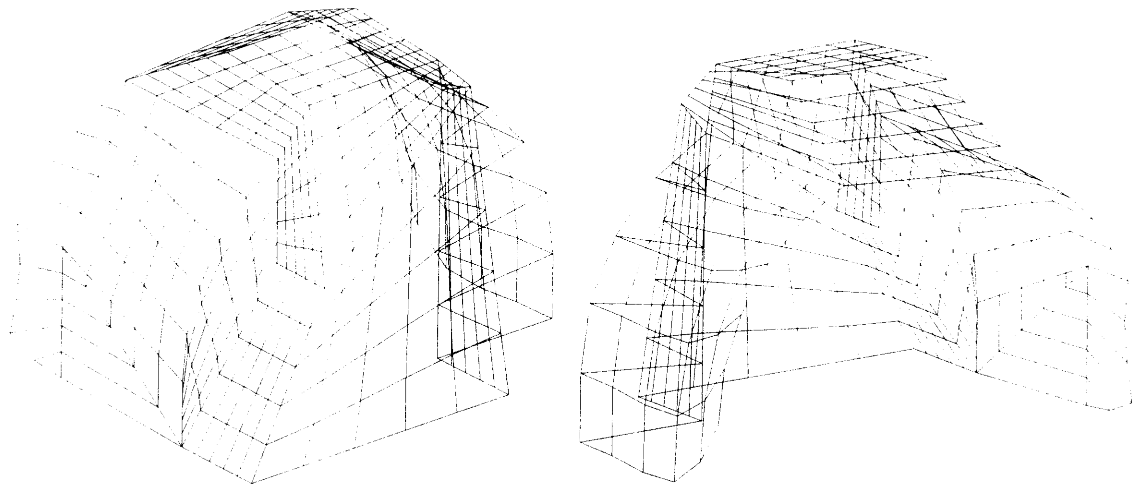
	RTM	TP Stamp
Capital cost/ part	$7.89	$4.67
Labor cost/part	$24.93	$4.17
Tooling cost/part	$9.13	$0.65
Material cost/part	$8.29	$19.69
Energy cost/part	$5.26	$0.29
Total cost/part	$60.00	$29.47
cost/lb	$9.68	$3.37
% Molding cap. used	46.85	86.81
% Preform cap. used	44.74	
Part weight (lbs)	6.20	8.75

Table 4-8. Firewall Manufacturing Costs

4.5.4 Conclusions

To restate what is rapidly becoming the norm, the substantial labor savings and capital savings derived from the rapid cycle time of the thermoplastic composite offer an advantage over RTM when the volume increases. The lower volume, 500/year application also demonstrates a possible superiority over RTM, but only if the entire vehicle assembly is based upon the thermoplastic manufacturing process, thereby using up the excess capacity.

4.6 Wheelwells



Wheelwell arch area: 670 in^2

Wheelwell shock tower area: 700 in^2

Total area: 1370 in^2

4.6.1 Performance Requirements

The most severe loading condition the wheelwell experiences, as noted above, is the 3 g vertical acceleration with inertial relief. This was simulated with an ANSYS finite element model (fig. 4-5).

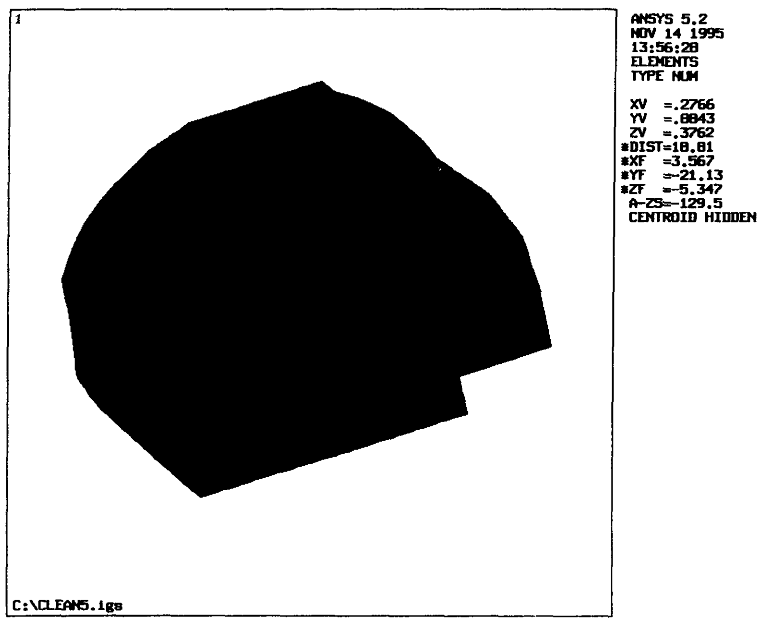


Figure 4-4. Finite Element Model of Wheelwell

The center of mass and the inertia around the center of mass of the various components of the vehicle (batteries, 4 passengers, motor, suspension, glass, etc.) were calculated using an Excel spreadsheet listing the location and weight of significant masses in the vehicle (see Appendix). A combination of lumped masses and volume moments of inertia was used. The inertia of the vehicle body was calculated using ANSYS and combined with the previous sums. The following are the results:

CG, X axis	-49 in.	(49 inches behind the front firewall)
CG, Z axis	9.5 in.	(9.5 inches above the floor)
X axis Moment of inertia	9200 in-lbs	
Y axis moment of inertia	34000 in-lbs	
Z axis moment of inertia	39300 in-lbs	

The mass of the vehicle was simulated with a lumped inertia/mass located at the CG of the vehicle and connected to the wheelwell attachment points with rigid links simulating the attachment area of the firewall and rocker box.

Under the load case described above, the material was required not to fail in fatigue. This was assured by incrementing the ply layups until the maximum stresses encountered in the finite element analysis (discounting the mathematical singularities found extremely close to the points of application of the vertical force) was below the endurance limit of the fiberglass material, 20 ksi[87].

4.6.2 Manufacturing Processes Examined

For the RTM design, various ply layups using 24 oz. woven roving were used in an iterative manner to determine a sufficient layup thickness to withstand the forces of the loading, resulting in 4 layers of alternating 0/45 alignment used in the arch section of the wheelwell and 6 layers (.228 in.) of alternating 0/45 alignment used in the shock tower section for the final design. This produced a final weight per wheelwell of (670*.152*.066) +(700*.228*.066) = 17.3 lbs.

The thermoplastic design used similar thicknesses of [0/90/±45] isotropic layups, with more plies required as the thickness of the unidirectional thermoplastic plies is only 0.0078 in. compared to the 0.038 in. thickness of the woven roving.

4.6.3 Manufacturing Results

RTM/TP stamping matched tooling cost: $175327

Manufacturing Costs: 2,000/year (4 per vehicle)

	RTM	TP Stamp
Capital cost/ part	$15.78	$4.79
Labor cost/part	$24.93	$4.17
Tooling cost/part	$19.61	$15.12
Material cost/part	$26.18	$41.92
Energy cost/part	$5.48	$0.29
Total cost/part	$91.99	$66.29
cost/lb	$5.32	$3.56
% Molding cap. used	65.59	4.34
% Preform cap. used	4.47	
Part weight (lbs)	17.30	17.3

Manufacturing Costs: 80,000/year (4 per vehicle)

	RTM	TP Stamp
Capital cost/ part	$15.78	$2.39
Labor cost/part	$29.65	$4.17
Tooling cost/part	$5.36	$0.38
Material cost/part	$26.18	$41.92
Energy cost/part	$5.01	$0.29
Total cost/part	$82.00	$49.15
cost/lb	$4.74	$2.64
% Molding cap. used	187.39	86.81
% Preform cap. used	89.47	
Part weight (lbs)	17.30	17.3

Table 4-9. Wheelwell Manufacturing Costs

4.6.4 Conclusions

The extremely high number of parts dictated by the use of symmetry for this part provides an excellent 'high volume suitability test' for the processes examined. For example, to meet the volume production requirements with RTM requires the use of no less than 14 molds/presses working on double shifts, entirely because of the high cycle time (30 minutes) of the process. The thermoplastic stamping process, however, meets the demand with only one mold and going to double shifts. This demonstrates why there is a much more pronounced drop in manufacturing costs with volume with thermoplastic stamping; a single press/RTM machine is only capable of about 7,500 parts per year working on double shift at maximum while a single press/TP machine has the potential for 115,000 parts/year and will have lower scrap rates as well due to the fact that a part can be reheated and restamped if it is not quite right the first time. Again, for initial startup, the RTM process may be more workable, but its limits will quickly be felt.

4.7 Dashboard/Rear seat

4.7.1 Performance Requirements

The dashboard is a secondary structure member whose purposes include location of instruments and controls for the driver, stabilization of the firewalls against buckling, and direction of bending forces from the battery box into the wheelwells. Exact figures for the surface area are not available, but can be roughly estimated by doubling the area of the firewall:

1000 in^2 (firewall area) * 2=2000 in^2

The rear seat is similar in functionality and area. Its primary purpose is simply to support the weight of any rear sear passengers. It is also used to help transmit bending loads from the battery box into the wheelwells.

4.7.2 Manufacturing Processes Examined

Thermoplastic stamping and resin transfer molding were the only processes in the study with the capability for the extremely complex, multicontoured surfaces of these components.

Load bearing requirements for both of these structures have been met experimentally by a quasisotropic material of thickness .125 in. Volume can be estimated at 250 in^3 and weight at .068 lb/in^3 density (randomly oriented PET/E glass) is 17 lbs or at .066 in/3 (polyester based) is 14.6 lbs.

Matched tools are assumed necessary for both resin transfer molding and thermoplastic stamping; despite the lack of direct structural requirements, these components require accurate surfaces on both sides for joining purposes and thus the more expensive tooling must be used.

4.7.3 Manufacturing Results

RTM/TP stamping matched tool cost: $217930

Manufacturing Costs/500:

	RTM	TP Stamp
Capital cost/ part	$15.78	$2.50
Labor cost/part	$24.93	$2.08
Tooling cost/part	$46.32	$74.49
Material cost/part	$21.30	$23.80
Energy cost/part	$6.20	$0.15
Total cost/part	$114.54	$103.02
cost/lb	$7.81	$6.06
% Mold cap. used	32.79	0.54
% Preform cap. used	2.24	
Part weight (lbs)	14.66	17

Manufacturing Costs/20000:

	RTM	TP Stamp
Capital cost/ part	$7.89	$2.50
Labor cost/part	$24.93	$2.08
Tooling cost/part	$13.21	$1.86
Material cost/part	$21.30	$22.95
Energy cost/part	$5.26	$0.15
Total cost/part	$72.60	$29.54
cost/lb	$4.97	$1.74
% Mold cap. used	46.85	21.70
% Preform cap. used	22.37	
Part weight (lbs)	14.66	17

Table 4-10. Dashboard/Rear Seat Manufacturing Costs

4.7.4 Conclusions

The lower price of the low performance thermoplastic material compared with the high performance material gives a higher advantage over the resin transfer molding process to the TP stamping process at high volumes. Also, the lower performance thermoplastic (as compared to oriented laminates) allows use a shorter 1 minute cycle time[88] as it has no need to consolidate multiple ply laminates.

Chapter 5

Crash Structure

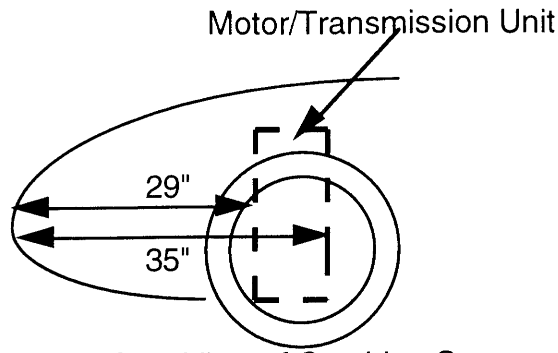
5.1 Crashworthiness-Frontal Impact/Angled Impact

The most important crashworthiness test the vehicle structure must meet is the 30 mph frontal barrier impact test. The frontal crash structure must also meet standards in a 30 mph 30 degree off-axis impact. Roof crush, rear impact, and side impact standards are also mandated by the National Highway Transportation Safety Administration (NHTSA) but will not be covered here as these are considered secondary to the frontal impact test.

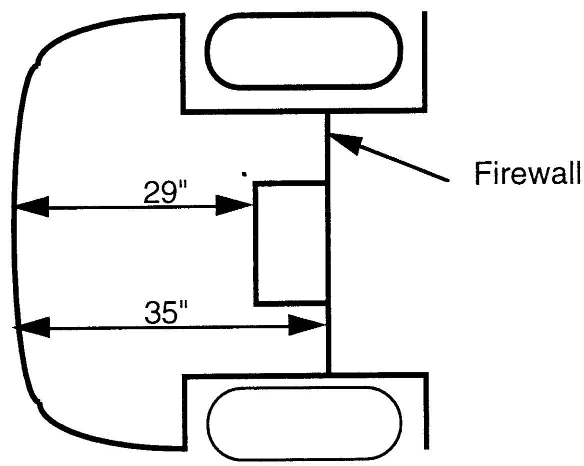
The primary requirement that must be met in the 30 mph fixed barrier frontal impact test is to limit the forces developed on seatbelted passengers to a maximum of 60 g's for a maximum of 3 milliseconds. The industry accepted practice for design that gives a high probability of passing this test is to design for 20g average crushing force. The design must also have capabilities for off axis impact in order to pass the off axis test, which must be taken into account even when designing for the frontal impact test as most of the composite crushing structures that are optimized for single direction crush performance become very unstable when subjected to off axis forces.

5.2 Packaging Requirements

The allowable packaging space was 29" in length, 30" in width, and 12" in height (see fig. 5-1) with some leeway in the height and width dimensions. The strut designs detailed below allow for a longer packaging space (35").



Side View of Crushing Space

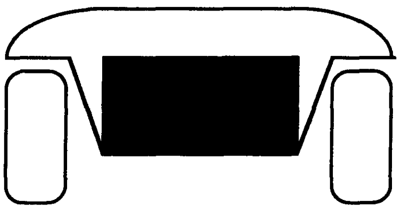


Top View of Crushing Space

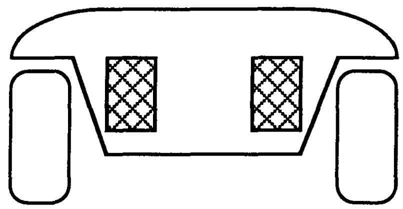
Figure 5-1. Side and Top View of Crushing Space

5.3 Concepts

Various concepts were considered. The most important are summarized here.

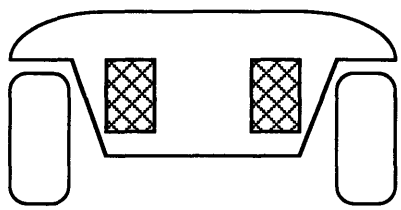


Foam Block (includes Elastomeric PU form composite, Macrosphere materials,

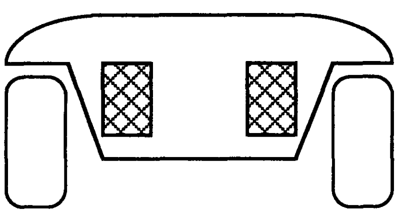


2 Foam Struts

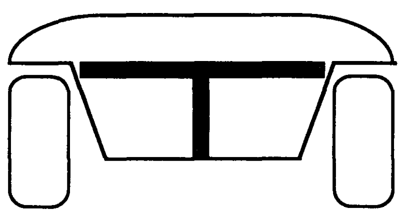
Honeycomb Block (including aluminum and Cecore plastic honeycomb)



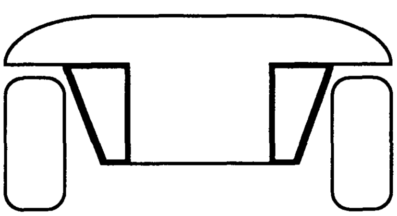
Honeycomb Struts (including aluminum and Cecore plastic honeycomb)



Balsa Struts



Fiberglass stiffened panels



Fiberglass struts or cones

Figure 5-2. Crash Design Concepts

5.4 Performance/Materials Selection

The basic first order crushing approximations used in the decision process were as follows:

Vehicle weight: 2400 lbs/g

Design crushing g's: 20

Crushing force: (2400 lbs/g)(20 g's)=48000 lbs crushing force

A variety of crushing materials were considered, with selection based on crush strength, cost, and crush performance. The crush strength of several of the materials considered is depicted in figs. 5-3 and 5-4.

Foam Block: polyurethane, Rohacell oriented foam, polystyrene, elastomeric PU

Polyurethane Foam

Using an industry supplied guide to polyurethane form crushing performance[89] and the following inputs:

Vehicle mass=(2400 lbs)/(32.2 ft/sec^2) =74.5 lbm

Energy=$\frac{1}{2}mv^2$=(0.5)(74.5 lbm)(44 ft/sec)^2=72,150 ft-lbs

Crush length=29 in.

Optimal g: 72,150 ft-lbs=(74.5 lbm)(x g's)(32.2 ft/sec^2/g)(29 in)(1 foot/12 in)

-->x= 12.4 g's in the gentlest possible deceleration case.

Optimal g is the gentlest possible deceleration, which assumes a perfectly uniform crushing force evenly distributed over the entire crushing length. From the industry guide, the ratio of the actual g's experienced to the optimal g's for polyurethane foam FR-3700 is typical 2.5 to 3. Thus the actual g's predicted are:

(12.4 g)(2.7)=33.5 g

Figure 5-3. Material Crush Strength: High Strength Materials

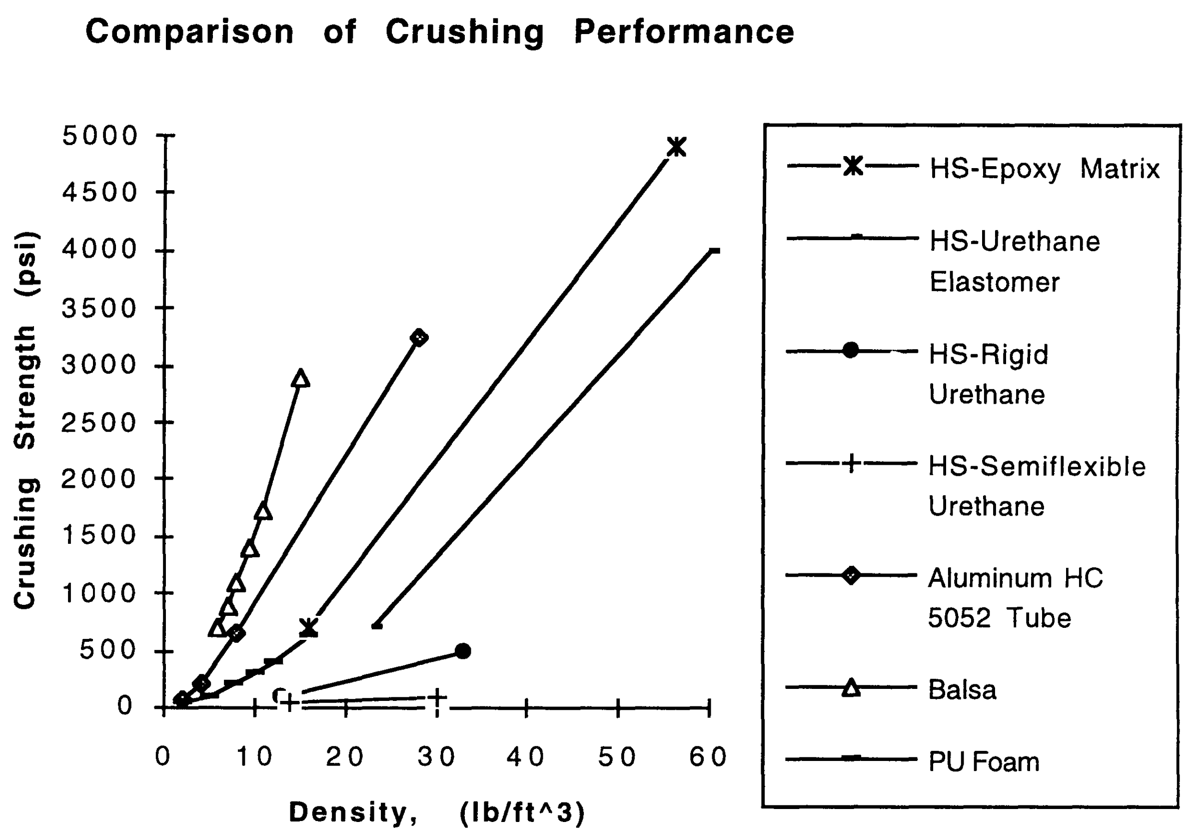
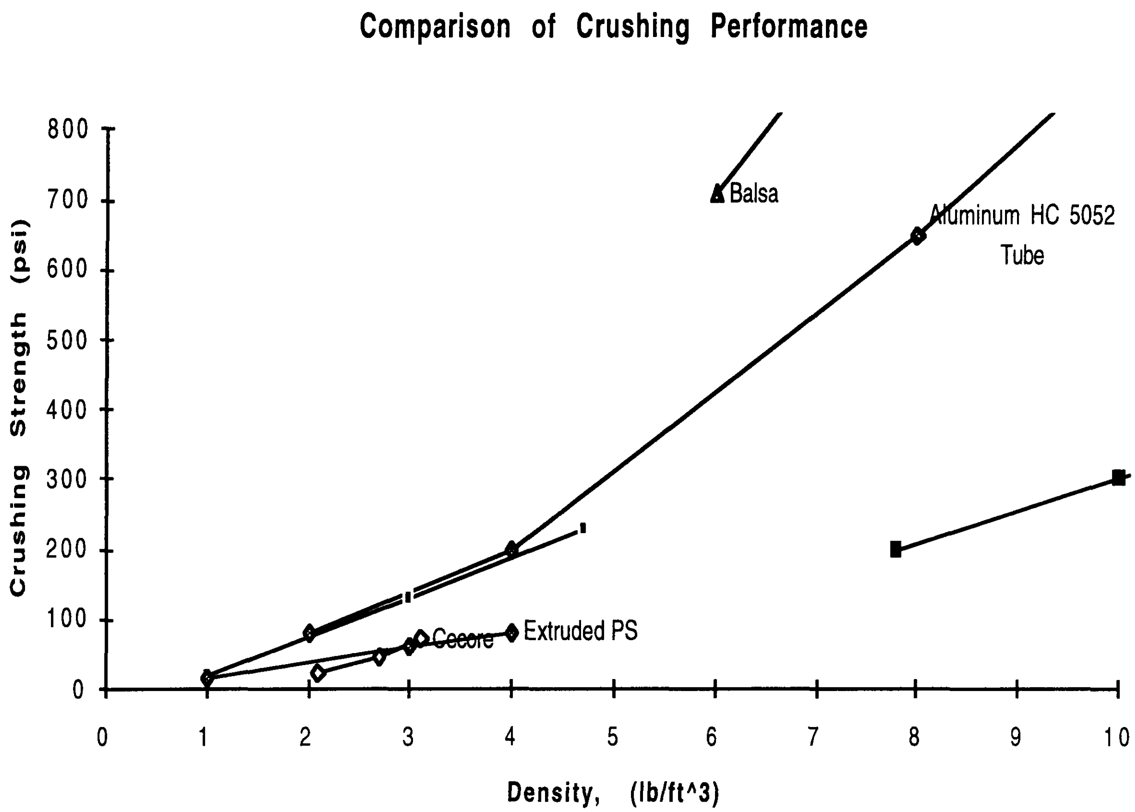


Figure 5-4. Material Crush Strength: Low Strength Materials



Thus the polyurethane foam block does not meet the performance requirements. The principle problem is that a general characteristic of foams in crush is a gradually increasing force vs. deflection behavior that suddenly becomes very steep at about the 60% crush area. This is because the foam 'packs up' and starts to behave more like a solid material, which provides for inefficient crush behavior in comparison to honeycomb, balsa, and stiffened panels.

Similar problems were expected with Rohacell foam, polystyrene foam, elastomeric polyurethane foam, and the macrosphere composites, so these design concepts were not pursued.

Foam Struts

With the foam strut design concept, the available crushing length is 35" as the struts can be placed on either side of the transmission case which is located in the center of the vehicle floor and is the reason for the previous 29" limitation. There is possible interference with the driveshafts, as they pierce the foam strut on their way from the engine to the wheels, but in a crushing situation the small void in the foam that is caused by the driveshafts is not considered crucial.

The struts were designed with the following dimensions to fit in the front compartment:

Length=35 in.

Width=8.5 in.

Height=4 in.

Going through calculations similar to the foam block above the minimum g obtainable from this design is 27 g, which does not meet the performance requirement.

Honeycomb Block

Commercial grade aluminum honeycomb is the least expensive grade and thus is the type most likely to meet the cost requirements of (15 lbs)($5/lb)=$75. Using an industry design chart[90] the following variables were input and the minimum packaging length calculated.

W=2400 lbs

V=44 ft/sec (@ 30 mph)

G=20 g's

A=384 in^2

It was found that the aluminum honeycomb was a marginal design option as the minimum crushing distance was 30 inches, slightly over the 29" packaging space. The weight was calculated at 15.6 lbs, which essentially meets weight requirements. The cost was roughly estimated at $300[91] for materials alone which is over the cost requirements. Cecore plastic honeycomb did not have sufficient crushing strength to succeed in this application and was discarded as a design option.

Honeycomb Struts

The previous analysis was repeated for honeycomb struts; using commercial grade aluminum honeycomb, the weight was calculated at 12.33 lb, which meets the target of 15 lbs. The cost was estimated at $100, which is somewhat over cost requirements but is still relatively viable. The main problem with a strut arrangement is off axis crushing, at which the struts tend to perform poorly.

Balsa struts

Calculations similar to those above showed that the principle problem with balsa struts is the extremely high crush strength (720 psi is the lowest commercially available). This causes the struts to be thinner than the aluminum struts, with a high possibility of simply snapping off in any crash situation other than in a perfectly oriented head on collision. However, their weight (8 lbs) and their cost ($10/car[92]) are very attractive; a good application for future work would be a balsa plate in place of the foam core of the T stiffened foam/fiberglass panel.

Fiberglass Stiffened Cones/Struts

These have been relatively extensively studied in the literature, to the point of creation of design guides for crushing frustra.[93] However, the same problem that was encountered with the honeycomb and balsa struts is also prevalent here; namely, the tendency to simply snap when confronted with an off-axis impact. The results of this can be seen in a paper[94] demonstrating an attempt to create an crushing strut that would crush at an angle to the oncoming impact. As is shown in the paper, the fiberglass/polyester strut simply snapped and was relatively ineffective at absorbing the shock. This concept was thus discarded.

Fiberglass Stiffened Panel

This was the design eventually settled upon. This design offers light weight (about 15 lbs), relative ease of manufacture translating into low cost (about $75), and the ability to absorb off axis impacts well. There is a dearth of design information for this design in crash behavior, and so initial attempts used a simple horizontal panel composed of 2" thick polyurethane foam with fiberglass skins on either side attached to either side of the front compartment with a similarly constructed vertical stiffener bracing it from the bottom.

5.5 Dynamic Test

This design was fabricated into a prototype nose and crash tested 1/95 with promising results. The force vs. time plots from the accelerometers attached to the crash sled displayed a nearly uniform crush behavior, closely approximating the optimal crush behavior of a horizontal line. Problems with the design that surfaced during testing included a relatively poor utilization of the top plate of the structure; it simply popped off as the structure was crushed. The lower panel, however, showed excellent utilization, with horizontal cracks every 3/8" or so showing how the panel had 'accordioned' during the crash, absorbing as much energy as possible through fracture of the matrix. This points to a possible higher utilization of the top panel by adding a rib or two to stiffen it.

A modified version of this design was assembled into a full scale prototype vehicle and successfully crash tested in 1995, passing the NHTSA frontal impact standards and is one of only a few composite structure vehicles to do so[95].

Chapter 6

Assembly

6.1 Adhesive Bonding

Adhesive bonding is the joining together of the separate pieces of the underbody to form a structural unit. The potential market for this is sufficiently large enough that manufacturers have developed special polymeric adhesives tailored for composite panel assembly. The example used for this part of the study is GenCorp's GEN-TAC^{R} 302 & 4001 Primerless Urethane Adhesive System. This base/hardener system is designed to bond fiber reinforced plastics together. Its properties include fast curing (60 seconds when heated above 250°F), high strength over the temperature ranges encountered in the automotive environment, the ability to bond composite to E-coated metal, and the ability to be used without the extensive surface preparation typically necessary for the aerospace adhesives. No surface abrasion is required, and typically only a 'dry rag wipe' is required to prepare the surface[96]. Cost at the 2500 lb/year supply rate is in the range of $2.90-$3.00/lb[97].

Using this information, a rough study of the costs to bond the chassis parts together was performed. Assembling the components into a fixture and applying the adhesive was estimated at 10 minutes/cycle (this assumes molded in ribs of 0.030" thickness in the part to provide proper adhesive thickness), the time to heat was taken (from above) as 60 seconds, and the time to remove the component was modeled with the Northrop ACCEM model[98]. The jig cost for each assembly operation was estimated by an engineer experienced in the field at $15,000. This analysis is necessarily somewhat more coarse than the analysis done for the previous components as the area of adhesive bonding is somewhat less well developed in terms of available data. The results for the 500/year production rate are shown below.

Adhesive Bonding	part area	bond area	assy. (hrs.)	heat (hrs.)	rmvl. (hrs.)	labr.@ $25/hr.	pounds adhsv.	cost/lb adhsv.	qty.	jig $/ year	total cost
Batt. box/flrpn	3752	1260	0.17	0.02	0.04	5.50	1.94	3.00	500	2500	16.31
rckr. box/flrpn	4052	1260	0.33	0.03	0.04	10.13	1.94	3.00	500	2500	20.94
frwlls./flrpn	2000	304	0.33	0.03	0.02	9.77	0.47	3.00	500	2500	16.17
whlwlls./flrpn	10000	368	0.67	0.07	0.07	20.09	0.57	3.00	500	2500	26.79

total adhsv. 2453 lbs/year total 80.20 $/car

Table 6-1. Adhesive Bonding Costs, 500/year

The results for 20,000/year are similar; only one set of jigs is required if the production goes to two shifts, and the jig cost is more fully amortized among the units:

Adhesive Bonding	part area	bond area	assy. (hrs.)	heat (hrs.)	rmvl. (hrs.)	labr.@ $25/hr.	pounds adhsv.	cost/lb adhsv.	qty.	jig $/ year	total cost
Batt. box/flrpn	3752	1260	0.17	0.02	0.04	5.50	1.94	3.00	20000	2500	11.43
rckr. box/flrpn	4052	1260	0.33	0.03	0.04	10.13	1.94	3.00	20000	2500	16.06
frwlls./flrpn	2000	304	0.33	0.03	0.02	9.77	0.47	3.00	20000	2500	11.29
whlwlls./flrpn	10000	368	0.67	0.07	0.07	20.09	0.57	3.00	20000	2500	21.91

total adhsv. 98110 lbs/year total 60.70 $/car

Table 6-2. Adhesive Bonding Costs, 20,000/year

6.2 Thermoplastic Welding

The ability of thermoplastic composites to be joined with welding methods is one of their primary advantages, as it avoids both the imprecision and the dependence on surface adhesion that characterizes thermoset adhesive bonding. Various methods are used for bonding thermoplastic composites: ultrasonic welding, hot-plate melting, spin/friction welding, and electromagnetic bonding. Of these, electromagnetic bonding is the only one suitable for the large complex bond lines and rapid cycle times required of the automotive industry.

The basic principle behind electromagnetic welding is the excitation of ferromagnetic particles embedded in a polymer matrix similar to the polymer used in the composite parts to be joined. This excitation is achieved by use of a generator connected to a work coil, which creates a magnetic field that acts upon the ferrous particles. While the adhesive material is molten, pressure is applied to the joint to achieve consolidation. During the process, the polymer from both contact surfaces melt and flow together with the polymer adhesive, achieving consolidation. The system considered here is an Emabond 2kW system, capable of bonding the size of joints encountered in this study in 15 seconds. The machine cost is $25,000 and the jigs and fixturing for a typical bond on the chassis (a 36" long, 2" wide, 3 sided bond between a firewall and the battery box) was estimated by Emabond engineers at $25,000 for a total of $50,000. The "Machine $/year" cell in the spreadsheet below was calculated by assuming use of a single power supply unit and 4 dedicated clamping stations, added together and amortized over an expected production run of 6 years. As mentioned previously, the cost model structure for the bonding is constructed in a different manner than the previous models as the bonding operation is not as standardized and the 15 second bond time would give an unrealistically low utilization based cost to the operation. Results are summarized in the following tables.

500/year

Electromag Welding	part area	bond area	assy. (hrs.)	heat (hrs.)	rmvl. (hrs.)	labr.@ $25/hr.	pounds adhsv.	cost/lb adhsv.	qty.	Mach $ /year	total cost
Batt. box/flrpn	3752	1260	0.17	0.004	0.04	5.18	1.42	6.50	500	5210	24.81
rckr. box/flrpn	4052	1260	0.33	0.008	0.08	10.46	1.42	6.50	500	5210	30.09
frwlls./flrpn	2000	304	0.33	0.008	0.05	9.74	0.34	6.50	500	5210	22.38
whlwlls./flrpn	10000	368	0.67	0.016	0.14	20.58	0.41	6.50	500	5210	33.70

total adhsv. 1796 lbs/year total 110.98 $/car

Table 6-3. Electromagnetic Bonding Costs, 500/year

20,000/year

Electromag Welding	part area	bond area	assy. (hrs.)	heat (hrs.)	rmvl. (hrs.)	labr.@ $25/hr.	pounds adhsv.	cost/lb adhsv.	qty.	Mach $ /year	total cost
Batt. box/flrpn	3752	1260	0.17	0.004	0.04	5.18	1.42	6.50	20000	5210	14.66
rckr. box/flrpn	4052	1260	0.33	0.008	0.08	10.46	1.42	6.50	20000	5210	19.93
frwlls./flrpn	2000	304	0.33	0.008	0.05	9.74	0.34	6.50	20000	5210	12.22
whlwlls./flrpn	10000	368	0.67	0.016	0.14	20.58	0.41	6.50	20000	5210	23.54

total adhsv. 71820 lbs/year total 70.34 $/car

Table 6-4. Electromagnetic Bonding Costs, 20,000/year

As can be seen, the higher volume benefits of the large production run are considerable. Further increases in production run would lower the cost of electromagnetic bonding more dramatically due to the extremely short cycle time of the process.

It should be noted that the relative costs of the two processes modeled here do not completely reflect the true situation. Traditional adhesive bonding is one of the major difficulties encountered in composite structures because of the requirement for relatively clean surfaces and the irreversibility of the process. In contrast, the electromagnetic welding process offers a clean, reversible, rapid, and proven joining technique that has already been used on automotive production volume levels[99]. Electromagnetic welding also offers a higher potential for robotic automation of the process due to its lack of reliance on unpredictable fluid flows and hand application of adhesive material to structural elements.

6.3 Consolidation Results

Bringing data together:

	Weight	Cost@500/yr.	Cost@20000/yr.
Top shell	200	$1,000.00	$1,000.00
Battery box			
RTM	91.7	$350.24	$210.07
Pultrude	94.1	$166.18	$116.21
Fil wind	96.5	$208.05	$164.89
Rocker boxes			
RTM	12.2	$103.23	$73.14
Pultrude	12.2	$42.19	$16.89
Floorpan			
RTM	48.8	$318.26	$149.95
Firewalls			
RTM	6.2	$95.07	$60.00
Wheelwell			
RTM	17.3	$91.99	$82.00
Dash/rear seat			
RTM	14.66	$114.54	$72.60
Thermoset based	478.22	2356	1893.14
Adhesive Bonding	4.91	80.20	60.70
Total Thermoset	483.13	$2,436.20	$1,953.84

Table 6-5. Thermoset Consolidation Cost Results

	Weight	Cost@500/yr.	Cost@20000/yr.
Top shell	200	$1,000.00	$1,000.00
Battery box			
TP stamp	70	$315.99	$171.88
TP wind	96.5	$337.11	$308.02
Rocker boxes			
TP stamp	12.2	$72.04	$42.14
Floorpan			
TP stamp	52.4	$436.76	$85.39
Firewalls			
TP stamp	8.75	$54.39	$29.47
Wheelwell			
TP stamp	17.3	$66.29	$49.15
Dash/rear seat			
TP stamp	17	$103.02	$29.54
TP stamping based	467.5	2476.81	1656.17
Inductive Welding	3.59	110.98	70.34
Total TP	471.09	$2,587.79	$1,726.51

Table 6-6. Thermoplastic Consolidation Cost Results

The optimum cost/weight choices for the thermoset vehicle were found to be:

Battery box: Pultruded

Rocker box: Pultruded

Remainder of primary structure: RTM

The optimum cost/weight choices for the thermoplastic vehicle were all found to be thermoplastic stamping based.

We can see that the thermoset based vehicle at 500/year will come in at $2436/vehicle finished cost at a weight of 483 lbs, which satisfies both our initial weight and cost targets. The thermoplastically stamped vehicle meets weight requirements at 471 lbs but at $2588/vehicle does not meet cost requirements at the lower production level. However, the TP stamped vehicle at $1727 surpasses the $1954 thermoset vehicle at the high volume production rate.

The thermoplastic vehicle also offers the promise of even lower costs as its price is so strongly dominated by the cost of the raw materials, which will decrease as capacity is increased to fulfill demand--$1.25/lb prepregging costs were assumed in this model while $0.25-$0.35/lb costs are encountered in prepregging SMC. The thermoset vehicle, however, derives much of its cost from the labor required to construct it; this high labor rate in turn is caused by the slow cycle times of the resin transfer molding process, which is itself limited by the speed of polymerization of the compounds used. Thus the thermoplastic method offers more future potential.

6.4 Comparison With Steel Vehicle Benchmark

As mentioned previously, both thermoset and thermoplastic construction methods were capable of meeting the cost and weight requirements stated at the beginning of the study. However, these must be taken in context with their competitor, the steel vehicle body. Comparison will be made both with an average of actual vehicles and with a new development, the Ultra Light Steel Auto Body developed by the ULSAB Consortium.

The reference vehicles used in the study by the Consortium were the Acura Legend, BMW 5-Series, Chevrolet Lumina, Ford Taurus, Honda Accord, Lexus LS400, Mazda 929, Mercedes 190E, and Toyota Cressida. These vehicles' average weight is 598 lbs and average cost is $1,116 U.S. (It should be noted that these weights and costs do not include doors, trunk, hood, front fenders, or front fascia, which the fiberglass vehicles' weights and costs do. Removing the doors, trunk, hood, and fenders lowers the composite vehicle weight by 80 lbs and the cost by $400, using the same wall thickness, density, and cost/lb assumptions that were made previously.) With this taken into account, the production weights and costs can be more clearly compared.

Vehicle	Weight (lbs)	Cost @ 500/year	Cost @ 20,000/year
Benchmark average	598	n/a	$1,116*
ULSAB	452	n/a	$962*
Thermoset	406	$2036	$1554
Thermoplastic	391	$2188	$1327

* cost of steel vehicles typically given at high production volumes of 100,000+/year

Table 6-7. Steel/Composite Weight and Cost Comparisons

From this information it can be concluded that while vehicles with composite structure do indeed cost more than all steel construction, the additional cost is not as high as that predicted by others if the structure is designed with manufacturability in mind. Furthermore, use of expensive carbon fibers is unnecessary to achieve light weight. Previous work had estimated the cost of an ultralight composite vehicle body shell to exceed $5000[100], which is 4x the present cost for a steel body. This estimate was based on the 420 lb GM Ultralight hand laid carbon fiber structure and used a material cost of $4/lb for carbon fiber/resin mixture. This ambitious goal for carbon fiber pricing was actually not unprecedented; Akzo-Fortafill had planned to market a high volume carbon fiber at this price prior to its purchase by Hercules Aerospace[101].

Furthermore, the composite vehicle has more room for improvement; simple substitution of carbon fiber for fiberglass in the central battery box allows the weight of the battery box to drop from 70 lbs to 35.6 lbs, at a price increase of $340.66 to $512.52 (based on current industrial carbon fiber prices of $18/lb) for the TP stamping at 20,000/year, which at $2,056 is under the $2,500/vehicle goal. This generates a total vehicle weight of 436.7 lbs. The cost/lb for the weight loss in this case is $10/lb, which is considered too expensive for commodity vehicles but is acceptable for high performance sporting vehicles such as the Corvette. No other structure in the vehicle is as highly loaded and has such potential for weight loss at relatively low cost increase via carbon fiber substitution; a fully carbon vehicle is neither affordable nor, as this study demonstrates, necessary. The cost of weight reduction can be expected to drop dramatically as carbon fibers become less expensive in volume production.

Chapter 7

Summary, Conclusions, and Further Work

7.1 Summary

A technique to design composite primary structure for moderate volume, high performance, cost conscious automotive applications has been developed. This resulted in a system for the design and manufacture of lightweight vehicles that are cost and performance competitive with the rest of the automotive industry, and is valuable for groups interested in designing such vehicles.

The cost and performance tradeoffs resulted in a vehicle using current thermoset technology and resins that provided a body-in-white weight reduction of 192 lbs or 35% over an average production vehicle at a cost increase of $438 or 39%. Based on volume price projections for thermoplastic matrix composite material, a vehicle could be constructed that achieved similar weight loss at a 17% cost increase, or $212. These prices are achievable at relatively low production levels of 20,000 vehicles/year, making this construction method ideal for the initially low-volume market of electric vehicles. Production weights and costs at two production levels are summarized in the table below.

Vehicle	Weight (lbs)	Cost @ 500/year	Cost @ 20,000/year
Benchmark average	598	n/a	$1,116*
ULSAB	452	n/a	$962*
Thermoset	406	$2036	$1554
Thermoplastic	391	$2188	$1327

* cost of steel vehicles typically given at high production volumes of 100,000+/year

The body-in-white weights shown above do not include doors, front fenders, front fascia, roof, or trunk panels; with these included the composite results are:

Vehicle	Weight (lbs)	Cost @ 500/year	Cost @ 20,000/year
Thermoset	486	2436	1954
Thermoplastic	471	2588	1727

7.2 Conclusions

This study provides several indications. High performance composite structures can be made in moderate volumes at a cost that is lower than that previously estimated, and inexpensive carbon fiber materials are not necessary for successful construction, although when they become available their use will assist in further weight reduction.

A combination of resin transfer molding and pultrusion offer the best cost and weight in off-the-shelf manufacturing processes and materials, while thermoplastic stamping offers the potential of much higher volume production at lower costs. An interesting attribute of thermoplastic stamping is the potential for the use of cast aluminum molds with elastomeric silicon mating halves to lower startup and tooling costs; a partnership with a thermoplastic materials supplier combined with these inaccuracy tolerant tools provides the greatest potential for a low-capital startup effort. RTM molds require carefully matched metal features and vacuum tightness, which precludes use of the cast aluminum/elastomeric plug molds.

Consumer fears about the inability of composite materials to successfully absorb crash energy and protect occupants are exaggerated; although the materials do present difficulties in the modeling and characterization of crushing behavior, a thorough testing program can result in successful crash performance.

7.3 Further Work

More work must be done before production work is begun, especially in the case of the thermoplastic materials, which have a far thinner history of characterization than do the thermosets. Risk reduction processing must be undertaken in the areas of high volume fraction, multiangle ply pultrusion; thermoplastic stamping of complex curvatures, electromagnetic bonding, and cycle time for thermoplastic stamping of relatively thick thermoplastic laminates. Thermoplastic pultrusion is an emerging technology that was not covered in this study but offers a high degree of potential and deserves study especially as much of the vehicle's structure depends upon components well suited to pultrusion.

Endurance testing should also be undertaken on the bonding agents and substrates indicated in this study to determine their suitability for extended use in automotive primary structure. A small scale experimental facility should be developed using inexpensive dies of cast aluminum or Kirksite before committing to the cost of machined matched tooling. Recyclability trials must be undertaken for both thermoplastic and thermoset composites. Once these conditions have been satisfactorily met, the composite structured vehicle will be well positioned to take a leading role in the efforts of urban pollution reduction.

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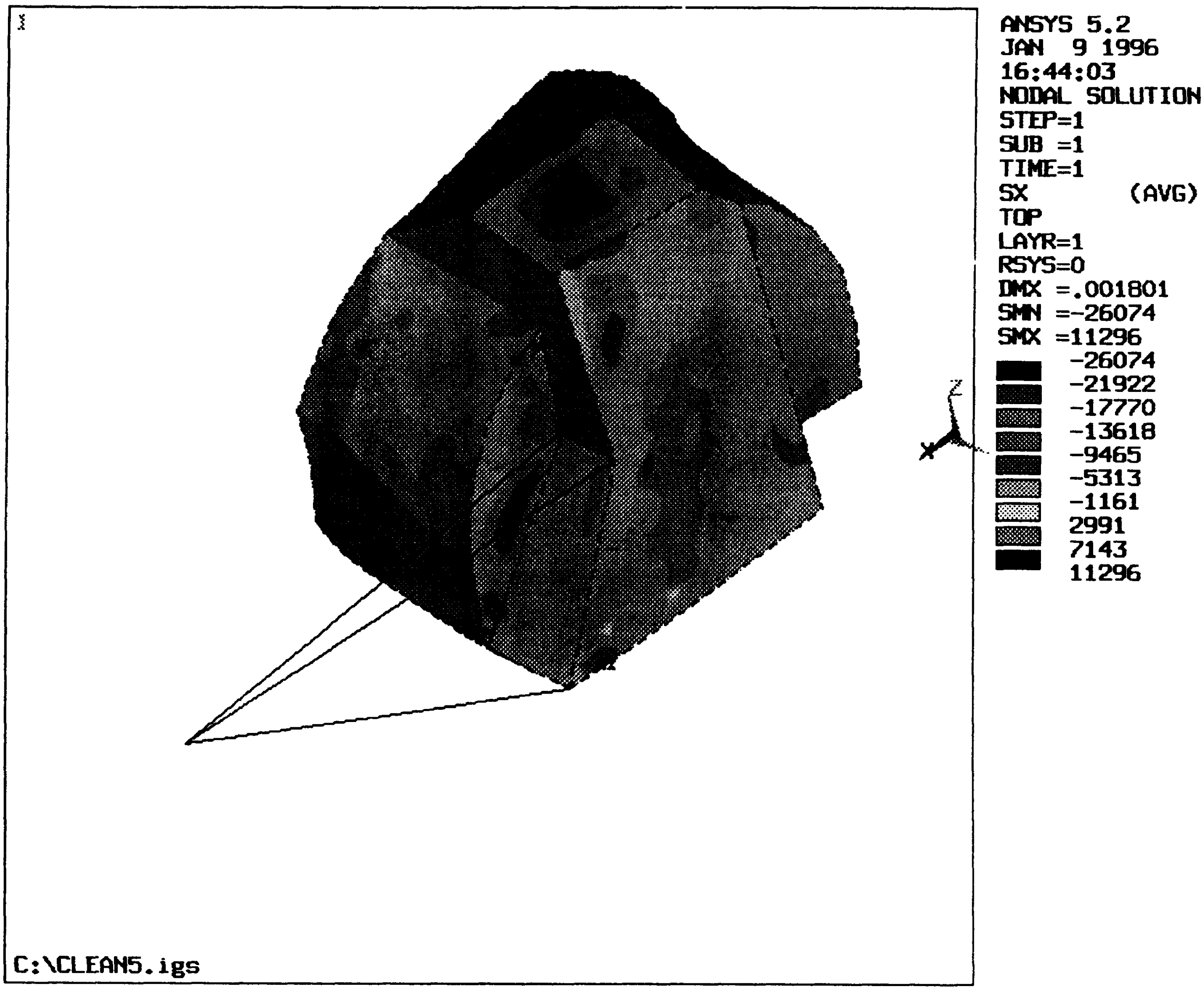
Appendix A: Wheelwell Finite Element Results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2991
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Appendix B: Complete Manufacturing Summary

Complete Mfg. Summary

Battery Box

500/year

	RTM	Fil. Wd.	Pult.	TP stamp	TP Fil. Wd.
Capital cost/ part	$15.78	$36.85	$0.89	$5.98	$27.91
Labor cost/part	$24.93	$40.18	$2.43	$4.17	$83.51
Tooling cost/part	$163.37	$4.00	$50.00	$147.81	$2.00
Material cost/part	$138.51	$115.71	$112.86	$157.74	$223.69
Energy cost/part	$7.65	$11.31	$0.00	$0.29	$0.00
Total cost/part	$350.24	$208.05	$166.18	$315.99	$337.11
cost/lb	$3.82	$2.16	$1.77	$4.51	$3.39
% molding used	16.40	41.85	1.27	1.09	86.99
% preforming used	1.12				
Part weight (lbs)	91.70	96.50	94.1	70	96.5

20,000/year

	RTM	Fil. Wd.	Pult.	TP stamp	TP Fil. Wd.
Capital cost/ part	$15.78	$7.63	$0.89	$5.98	$0.82
Labor cost/part	$24.93	$40.18	$1.22	$4.17	$83.51
Tooling cost/part	$25.59	$0.12	$1.25	$3.70	$0.00
Material cost/part	$138.51	$115.71	$112.86	$157.74	$223.69
Energy cost/part	$5.26	$1.26	$0.00	$0.29	$0.00
Total cost/part	$210.07	$164.89	$116.21	$171.88	$308.02
cost/lb	$2.29	$1.71	$1.24	$2.45	$3.10
% molding used	93.69	93.00	50.64	43.40	96.66
% preforming used	44.74				
Part weight (lbs)	91.70	96.5	94.1	70	96.5

Rocker Boxes

1,000/year (2/car)

	RTM	TP Stamp	Pult.
Capital cost/ part	$15.78	$5.00	$0.68
Labor cost/part	$24.93	$4.17	$1.86
Tooling cost/part	$39.90	$30.67	$25.00
Material cost/part	$16.42	$31.91	$14.65
Energy cost/part	$6.20	$0.29	$0.00
Total cost/part	$103.23	$72.04	$42.19
cost/lb	8.46	$5.08	$3.46
% Molding cap. used	32.79	2.17	1.94
% Preform cap. used	2.24		
Part weight (lbs)	12.20	12.2	12.2

Complete Mfg. Summary

40,000/year (2/car)

	RTM	TP Stamp	Pult.
Capital cost/ part	$15.78	$5.00	$0.68
Labor cost/part	$24.93	$4.17	$0.93
Tooling cost/part	$10.71	$0.77	$0.63
Material cost/part	$16.45	$31.91	$14.65
Energy cost/part	$5.26	$0.29	$0.00
Total cost/part	$73.14	$42.14	$16.89
cost/lb	6.00	$2.97	$1.38
% Molding cap. used	93.69	86.81	77.55
% Preform cap. used	89.47		
Part weight (lbs)	12.20	12.2	12.2

Floorpan

500/year

	RTM	TP Stamp
Capital cost/ part	$15.78	$3.43
Labor cost/part	$24.93	$2.08
Tooling cost/part	$197.49	$357.69
Material cost/part	$72.42	$73.42
Energy cost/part	$7.65	$0.15
Total cost/part	$318.26	$436.76
cost/lb	$6.52	$8.33
% Molding cap. used	16.40	0.54
% Preform cap. used	1.12	
Part weight (lbs)	48.80	52.4

20,000/year

	RTM	TP Stamp
Capital cost/ part	$15.78	$3.43
Labor cost/part	$24.93	$2.08
Tooling cost/part	$31.56	$8.94
Material cost/part	$72.42	$70.80
Energy cost/part	$5.26	$0.15
Total cost/part	$149.95	$85.39
cost/lb	$2.77	$1.63
% Molding cap. used	93.69	21.70
% Preform cap. used	44.74	
Part weight (lbs)	48.80	52.4

Complete Mfg. Summary

Firewalls

1,000/year (2/car)

	RTM	TP Stamp
Capital cost/ part	$15.78	$4.67
Labor cost/part	$24.93	$4.17
Tooling cost/part	$35.37	$25.57
Material cost/part	$8.29	$19.69
Energy cost/part	$6.20	$0.29
Total cost/part	$95.07	$54.39
cost/lb	$15.33	$6.22
% Molding cap. used	32.79	2.17
% Preform cap. used	2.24	
Part weight (lbs)	6.20	8.75

40,000/year (2/car)

	RTM	TP Stamp
Capital cost/ part	$7.89	$4.67
Labor cost/part	$24.93	$4.17
Tooling cost/part	$9.13	$0.65
Material cost/part	$8.29	$19.69
Energy cost/part	$5.26	$0.29
Total cost/part	$60.00	$29.47
cost/lb	$9.68	$3.37
% Molding cap. used	46.85	86.81
% Preform cap. used	44.74	
Part weight (lbs)	6.20	8.75

Wheelwells

2,000/year (4/car)

	RTM	TP Stamp
Capital cost/ part	$15.78	$4.79
Labor cost/part	$24.93	$4.17
Tooling cost/part	$19.61	$15.12
Material cost/part	$26.18	$41.92
Energy cost/part	$5.48	$0.29
Total cost/part	$91.99	$66.29
cost/lb	$5.32	$3.56
% Molding cap. used	65.59	4.34
% Preform cap. used	4.47	
Part weight (lbs)	17.30	17.3

Complete Mfg. Summary

80,000/year (4/car)

	RTM	TP Stamp
Capital cost/ part	$15.78	$2.39
Labor cost/part	$29.65	$4.17
Tooling cost/part	$5.36	$0.38
Material cost/part	$26.18	$41.92
Energy cost/part	$5.01	$0.29
Total cost/part	$82.00	$49.15
cost/lb	$4.74	$2.64
% Molding cap. used	187.39	86.81
% Preform cap. used	89.47	
Part weight (lbs)	17.30	17.3

Dashboard

500/year

	RTM	TP Stamp
Capital cost/ part	$15.78	$2.50
Labor cost/part	$24.93	$2.08
Tooling cost/part	$46.32	$74.49
Material cost/part	$21.30	$23.80
Energy cost/part	$6.20	$0.15
Total cost/part	$114.54	$103.02
cost/lb	$7.81	$6.06
% Mold cap. used	32.79	0.54
% Preform cap. used	2.24	
Part weight (lbs)	14.66	17

20,000/year

	RTM	TP Stamp
Capital cost/ part	$7.89	$2.50
Labor cost/part	$24.93	$2.08
Tooling cost/part	$13.21	$1.86
Material cost/part	$21.30	$22.95
Energy cost/part	$5.26	$0.15
Total cost/part	$72.60	$29.54
cost/lb	$4.97	$1.74
% Mold cap. used	46.85	21.70
% Preform cap. used	22.37	
Part weight (lbs)	14.66	17

Complete Mfg. Summary

Rear Seat

500/year

	RTM	TP Stamp
Capital cost/ part	$15.78	$2.50
Labor cost/part	$24.93	$2.08
Tooling cost/part	$46.32	$74.49
Material cost/part	$21.30	$23.80
Energy cost/part	$6.20	$0.15
Total cost/part	$114.54	$103.02
cost/lb	$7.81	$6.06
% Mold cap. used	32.79	0.54
% Preform cap. used	2.24	
Part weight (lbs)	14.66	17

20,000/year

	RTM	TP Stamp
Capital cost/ part	$7.89	$2.50
Labor cost/part	$24.93	$2.08
Tooling cost/part	$13.21	$1.86
Material cost/part	$21.30	$22.95
Energy cost/part	$5.26	$0.15
Total cost/part	$72.60	$29.54
cost/lb	$4.97	$1.74
% Mold cap. used	46.85	21.70
% Preform cap. used	22.37	
Part weight (lbs)	14.66	17

Appendix C: Vehicle Weight/Inertia Breakdown

Inertia Worksheet

Weights sufficiently far from axis in question are modeled as lumped masses.
Weights close to or on axis are modeled using volume inertias.
Not all weights used to calculate inertia are listed to simplify spreadsheet

SAE standard xyz coordinates: x axis front-back (0 at firewall,+forward),
y axis side-side (0 at center,+toward passenger side, and z axis up/down(0 at floor,+upward)

					x axis sum	y axis sun	z axis sum
					9170	33916	39284
		Position				inertia	
Item	Weight	X	Y	Z	x axis	y axis	z axis
					(y dist)	(x dist)	(x2+y2)^.5
Batteries (12)	414	-57	0	6	26	256	256
Body/Chassis	440	from FEA model			7570	29212	33373
People	600				506	441	948
Doors	40	-42	32	18	160	6	166
Drive System	**130**				13	1081	1081
Transmission	31	6	-9	16			
Drive Pulley	4.25	6.6	0	4			
Drive shaft	16	6.6	0	4			
Motor	72	6	5	16			
Power System	**30**				3	268	268
Drive Controller	21	20	0	10			
Charger	9	-120	-20	10			
HVAC	**41.7**				14	387	387
A/C compressor	5	-8	0	20			
A/C condensor	7	-8	0	20			
Driver motor	18	-8	0	20			
Evaporator	6	-8	20	20			
Heater box	5.7	-8	0	20			
Interior carpet	8	-57	0	6			
Jack & handle	5	-120	0	5			
Spare tire	19	-120	0	5			

Inertia Worksheet

Front Seats	64	-54	18	12	54	14	14
Rear seats back	24	-80	18	12	20	30	30
Front Suspension	**128**				347	1062	1408
Wheel/Tire (2)	62	6.6	32	4			
Lower swing arm (2)	20	6.6	32	0			
Strut assembly (2)	12	6.6	32	14			
Hubs/carrier (2)	14	6.6	32	4			
Springs (2)	20	6.6	32	14			
Rear Suspension	**120.1**				325	732	1057
Wheel/tire (2)	62	-102	32	4			
Strut assembly (2)	12	-102	32				
Trailing Link (2)	5.82	-96	32				
Lateral links (4)	6.28	-102	32				
Hubs/ carrier (2)	14	-102	32				
Springs (2)	20	-102	32	14			
Windows	**77**				132	428	296
Windshield	39	-8.2	0	35			
Door glass (2) *	22	-42	36	34			
Quarter glass (2) *	10	-80	36	34			
Rear glass *	6	-110	0	36			

Appendix D: CLPT Code

```
# For use with Maple V software

with (linalg):

 q:=matrix(3,3):
 s:=matrix(3,3):
 result1:=matrix(3,3):
 t:=matrix(3,3):
 tinv:=matrix(3,3):
 r:=matrix(3,3):
 rinv:=matrix(3,3):
 a:=matrix(3,3):
 temp:=matrix(3,3):
 qb:=matrix(3,3):
 sigmabar:=vector(3):
 sigma:=vector(3):

 El:=vector(6):
 Et:=vector(6):
 nult:=vector(6):
 Glt:=vector(6):
 Cost:=vector(6):
 nutl:=vector(6):

 numplies:=3:
 theta:=vector(numplies):
 h:=vector(numplies):
 qbar:=array(1..3,1..3,1..numplies):
 mat:=ivector(numplies):

 n:=vector(3):
 epsilon:=vector(3):
 ainv:=matrix(3,3):

 # initialize variables

 # Carbon fiber/epoxy prepreg

 El[1]:=139000000000:
 Et[1]:= 9700000000:
 nult[1]:=.29:
 Glt[1]:= 4900000000:
 Cost[1]:=220:
 nutl[1]:=nult[1]*Et[1]/El[1]:

 # Cracked Carbon fiber/epoxy prepreg

 El[2]:=139000000000:
 Et[2]:=    9700000:
```

```
nult[2]:=.00029:
Glt[2]:=   4900000:
Cost[2]:=220:
nutl[2]:=nult[2]*Et[2]/El[2]:

# Thermoplastic PET/Eglass
El[3]:= 6800000:
Et[3]:= 2000000:
nult[3]:=.29:
Glt[3]:= 800000:
Cost[3]:=2:
nutl[3]:=nult[3]*Et[3]/El[3]:

# 24 oz woven roving/polyester
El[4]:= 3000000:
Et[4]:= 3000000:
nult[4]:=.12:
Glt[4]:= 600000:
nutl[4]:=nult[4]*Et[4]/El[4]:

# unidirectional roving/polyester
# assuming 55% vol fraction, AIAA book

El[5]:= 6300000:
Et[5]:= 1200000:
nult[5]:=.26:
Glt[5]:= 600000:
nutl[5]:=nult[5]*Et[5]/El[5]:

# thermoplastic carbon/nylon 6

El[6]:= 16.0e6:
Et[6]:= 1.1e6:
nult[6]:=.28:
Glt[6]:=.74e6:
nutl[6]:=nult[6]*Et[6]/El[6]:

# initialize n vector

n[1]:=0:
n[2]:=0.:
n[3]:=150:

# set theta and h (thickness) for each layer (only
# 4 are defined to use symmetry)

theta[1]:=3.141592/4.:
h[1]:=.0312:
mat[1]:=6:
```

```
 theta[2]:=-3.141592/4.:
 h[2]:=.0312:
 mat[2]:=6:

 theta[3]:=0:
 h[3]:=.0312:
 mat[3]:=6:

# theta[4]:=3.14159/4:
# h[4]:=.000965:
# mat[4]:=4:

 # sum thicknesses

 thickness:=0:

 for i from 1 to numplies do
  thickness:=thickness+2*h[i]:
 od:

 for i from 1 to 3 do
  for j from 1 to 3 do
   a[i,j]:=0:
  od:
 od:

 # define q, r, and rinverse matrices
 # loop through layers, adding each successive layer's q
 # matrix multiplied by h

 for layer from 1 to numplies do

 matnum:=mat[layer]:
 print(matnum);

 q[1,1]:=El[matnum]/(1-nult[matnum]*nutl[matnum]);
 q[1,2]:=(nutl[matnum]*El[matnum])/(1-nult[matnum]*nutl[matnum]);
 q[1,3]:=0;
 q[2,1]:=(nult[matnum]*Et[matnum])/(1-nult[matnum]*nutl[matnum]);
 q[2,2]:=Et[matnum]/(1-nult[matnum]*nutl[matnum]);
 q[2,3]:=0:
 q[3,1]:=0:
 q[3,2]:=0:
 q[3,3]:=Glt[matnum];

 r[1,1]:=1.:
 r[1,2]:=0:
 r[1,3]:=0:
```

```
r[2,1]:=0:
r[2,2]:=1.:
r[2,3]:=0:
r[3,1]:=0:
r[3,2]:=0:
r[3,3]:=2.:

rinv[1,1]:=1.:
rinv[1,2]:=0:
rinv[1,3]:=0:
rinv[2,1]:=0:
rinv[2,2]:=1.:
rinv[2,3]:=0:
rinv[3,1]:=0:
rinv[3,2]:=0:
rinv[3,3]:=.5:

t[1,1]:=cos(theta[layer])*cos(theta[layer]):
t[1,2]:=sin(theta[layer])*sin(theta[layer]):
t[1,3]:=2*sin(theta[layer])*cos(theta[layer]):
t[2,1]:=sin(theta[layer])*sin(theta[layer]):
t[2,2]:=cos(theta[layer])*cos(theta[layer]):
t[2,3]:=-2*sin(theta[layer])*cos(theta[layer]):
t[3,1]:=-sin(theta[layer])*cos(theta[layer]):
t[3,2]:=sin(theta[layer])*cos(theta[layer]):
t[3,3]:=cos(theta[layer])*cos(theta[layer])-sin(theta[layer])*sin(theta[layer]):

tinv[1,1]:=cos(theta[layer])*cos(theta[layer]):
tinv[1,2]:=sin(theta[layer])*sin(theta[layer]):
tinv[1,3]:=-2*sin(theta[layer])*cos(theta[layer]):
tinv[2,1]:=sin(theta[layer])*sin(theta[layer]):
tinv[2,2]:=cos(theta[layer])*cos(theta[layer]):
tinv[2,3]:=2*sin(theta[layer])*cos(theta[layer]):
tinv[3,1]:=sin(theta[layer])*cos(theta[layer]):
tinv[3,2]:=-sin(theta[layer])*cos(theta[layer]):
tinv[3,3]:=cos(theta[layer])*cos(theta[layer])-sin(theta[layer])*sin(theta[layer]):


temp:=multiply(tinv,q,r,t,rinv);
# transfer to qbar array

for i from 1 to 3 do
  for j from 1 to 3 do
    qbar[i,j,layer]:=temp[i,j]:
  od:
od:

for i from 1 to 3 do
  for j from 1 to 3 do
```

```
    # 2 multiplier in next line is because of symmetry

    a[i,j]:=a[i,j]+2*qbar[i,j,layer]*h[layer]:

  od:
 od:

 od:

 # invert a matrix and solve for strain vector epsilon
 print (a);

 ainv:=inverse(a):

 epsilon:=multiply(ainv, n);


 # now solve for engineering constants of laminate

 E1:=1./(ainv[1,1]*thickness);
 E2:=1./(ainv[2,2]*thickness);
 E6:=1./(ainv[3,3]*thickness);

 nutl:=-ainv[1,2]/ainv[2,2];


 for i from 1 to numplies do


sigmabar[1]:=qbar[1,1,i]*epsilon[1]+qbar[1,2,i]*epsilon[2]+qbar[1,3,i]*epsilon[3]:

sigmabar[2]:=qbar[2,1,i]*epsilon[1]+qbar[2,2,i]*epsilon[2]+qbar[2,3,i]*epsilon[3]:

sigmabar[3]:=qbar[3,1,i]*epsilon[1]+qbar[3,2,i]*epsilon[2]+qbar[3,3,i]*epsilon[3]:

 t[1,1]:=cos(theta[i])*cos(theta[i]):
 t[1,2]:=sin(theta[i])*sin(theta[i]):
 t[1,3]:=2*sin(theta[i])*cos(theta[i]):
 t[2,1]:=sin(theta[i])*sin(theta[i]):
 t[2,2]:=cos(theta[i])*cos(theta[i]):
 t[2,3]:=-2*sin(theta[i])*cos(theta[i]):
 t[3,1]:=-sin(theta[i])*cos(theta[i]):
 t[3,2]:=sin(theta[i])*cos(theta[i]):
 t[3,3]:=cos(theta[i])*cos(theta[i])-sin(theta[i])*sin(theta[i]):


  sigma:=multiply(t,sigmabar):
  print(i, sigma);
```