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Design of a composite monocoque frame racing wheelchair

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Abstract—Design of present-day racing wheelchairs developed out of necessity and common sense. The chairs first used in racing were everyday chairs; through years of trial and modification the racing chairs of today evolved. Very little advanced engineering has been applied to the design of racing chairs. The Finite Element Analysis model executed on a computer provided insight into structural problem areas in the design of unibody frame racing chairs. Slight modifications to the model can be used to investigate new shapes, loads, or materials without investing large amounts of time and money. Wind tunnel testing with scale models provided perspectives on different improvements to reduce drag. Shape improvements may play an important role in reducing the racer's time during competition. Shape may help to decrease drag for the user in either the upright or down position. Considering that the frontal area increases around 30% in the up position with current strut and chassis frames, monocoque shapes should excel. Finite element analysis and air drag analysis are important to the design of a composite racing wheelchair. Composite materials may promote more efficient and ergonomic racing wheelchairs.

Key words: *aerodynamics, composite materials, ergonomics, finite element analysis, racing wheelchair, wheelchair design.*

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INTRODUCTION

Design for present-day racing wheelchairs developed out of necessity and common sense. The chairs first used in racing were everyday chairs; through years of trial and modification the race chairs of today evolved. It was hypothesized that their design could be greatly improved by applying modern engineering. A literature search was used to identify how engineering technology could best be applied. Using available engineering tools, a chair was designed and a monocoque prototype built. A monocoque vehicle is one in which the body is integral with the chassis. This paper presents a detailed design methodology and rationale for a composite monocoque frame racing wheelchair.

Importance of Designing Better Race Chairs

Approximately one spinal cord injury occurs every 45 minutes in the United States. Excluding all the cerebral palsy, muscular dystrophy, and other mobility-impairing diseases, that alone translates to about 10,000 new wheelchair users per year (1). Sports and competition are just as important to persons with disabilities as to "able-bodied" people, if not more so (1,2,3,4,5,6). Competition helps maintain an individual's fitness while improving feelings of self-worth. Lack of physical fitness can result in obesity and cardiorespiratory ailments to which chair users are particularly prone (1). Sports have proven to be an effective way to keep fit; improving the design of the equipment can help

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decrease the incidence of sports-related injuries. In turn, improved sports equipment will lead to improved everyday equipment (2,7,8,9). Technology developed to enhance the performance of racing chairs may someday become both realizable and affordable for use in everyday chairs. Increased mobility for persons with disabilities will help them overcome the stereotypes imposed upon them by society. The chair should not limit the individual.

History and Rules of Wheelchair Racing

Wheelchair racing was first introduced in 1948 (10). The first chairs were simply modified everyday chairs. Racing did not grow significantly in popularity until 1975, when Bobby Hall competed in his first marathon (7,10). Since then, wheelchair athletes have accomplished under 1-hour and 30-minute marathons and 4-minute miles (2). Some athletes support themselves with prize money from their racing (7).

The National Wheelchair Athletic Association (NWAA), which is the governing body regulating all wheelchair sports in the United States, has developed a set of rules governing allowable designs of racing chairs. In a wheelchair race, the object is to propel a wheelchair equipped with push-rings over a predesignated course in a minimum amount of time (11).

Chairs are required to have at least three wheels. The rear wheels are permitted a maximum diameter of 70 cm; the front wheel(s) are limited to a maximum diameter of 50 cm. Each rear wheel is allowed to have only one push-ring. The greatest width of the chair must be measured either at the wheels or the push-rings. The chair cannot rely on any chains, levers, or gears for propulsion; it must be propelled directly through the push-rings. Any structures for the sole purpose of gaining aerodynamic advantage are prohibited. All of the driver's limbs must be stable or securely fastened to avoid injury and the possibility of the driver falling out. The chair must be structurally sound to preclude catastrophic failure during a race (3).

Racing Wheelchair Design Parameters

Many factors influence the effectiveness of a racing wheelchair design: weight, materials, design, physical dimensions, fitness and ability of the user, interface compatibility between chair and user, as well as many external factors such as road surface and terrain (12). A description of some of the technologies in use or available for use to improve racing wheelchair design follows.

The Frame. The basic frame structure of the chair should provide good positioning of the pilot for better aerodynamics, propulsion ergonomics, and torso support. It must also be maneuverable and moderately stable, as well as stiff, to promote efficient transmission of energy to the wheels. Two main frame types have evolved so far, the cage seat and the bucket seat. Both incorporate a nonadjustable box design to help maintain the desired stiffness with light weight. The cage frame, being closed, can be made slightly stiffer. The bucket seat frame is open across the front allowing easier access; it is often preferred by quadriplegic persons (13). The frame struts should fit snugly to the sides of the user's chest and hips during propulsion. Side guards may be added to help protect the user from the wheels (3).

The chair's front end can be supported by either a cantilever or a fork wheel mount. Each requires "trail" (i.e., the distance between the contact point of the front wheel with the road surface to the extension of the pivot axis to the road surface) to keep the steering mechanism stable (13). A light front end permits the user to make minor steering adjustments easily (3). If the front becomes too light, the chair may easily tip into a "wheelie" during acceleration.

Frame size is determined by the user's body dimensions and stability requirements. The width must allow easy access to the push-rings for propulsion, while providing a stable wheelbase (14). Cambering the wheels can help increase the effective wheelbase track and improve pushing ergonomics. The wheelbase is also dependent on chair length. Long chairs are dynamically more stable, while short chairs have been found to have superior performance in short races and can also "draft" behind other chairs more effectively (15,16).

Seat Position. The pilot's position substantially affects the handling characteristics of the chair. Positioning the center of gravity is an important factor in race chair design. Presently, positioning decisions are made using a few rules of thumb and trial and error (7). Most seats consist of a nylon or cloth sling with straps, which positions the user ergonomically and aerodynamically while helping to remove unwanted motions. A knees-up position

helps gain more driving force while giving some upper-torso support (3). This support should not be so much that it restricts the motions required for propulsion. Other important seat dimensions include the seat-to-back angle and back height; these control the degree of support that the user has during propulsion. Some attempts to make an adjustable seat include a "hill climber" position (13).

The fore and aft position of the seat determines where the center of gravity falls relative to the wheelbase. A forward position helps to distribute the load over all the wheels. Positioning the seat too far forward can result in poor stroke kinematics, increased resistance in the steering, and a large downhill turning tendency. A good rule of thumb puts the center of gravity somewhere over the back third of the wheelbase (17). Downhill turning tendency occurs when the center of gravity is forward of the main wheels and the chair is on a side slope or crowned road. Its magnitude depends on wheelbase, steering mechanism, total mass of the chair and user, and their center of gravity. This creates a moment arm which causes the chair to turn downhill. Moving the center of gravity over the main wheels removes the moment arm but causes the chair to lose its directional stability (18,19). To correct these problems, chairs now include a compensator connected to the steering mechanism. There are three major types of compensators defined by the function of the springs: push-push, push-pull, and pull-pull. Pull-pull is the least effective; the other two are equally acceptable (12). Probably the most important seating consideration is body position relative to the push-rings. The user's shoulders should be slightly forward of the push-rings in order to employ the correct muscles. This enables efficient propulsion and minimizes the possibility of injury. This position depends on the user's skill and anthropometric measures, push-ring size, and the type of competition being raced (2,4,16,20).

The Wheels. Depending on the user's reach, strength, and experience, a 65–70 cm rear wheel is usually used. Smaller wheels, though easier to propel (e.g., they require less torque), can result in lower top speed. Two tire types are available: clinchers and sew-ups; the latter are slightly lighter and more expensive (13).

Spokes play an important role in the aerodynamics of the wheel. As they spin, the spokes mix up the air, creating turbulence. Reducing the number of spokes can reduce turbulence. However, using fewer spokes also decreases the wheel's strength and stiffness. This can be compensated for by lacing spokes radially instead of crossed (14). Spoke cross-sections can be flat or elliptical to increase their ability to cut through air. Some modern designs use a three-spoke or a monospoke wheel. The monospoke resembles a solid disk; more expensive and heavier, it is also faster, stiffer, and may possibly reduce injuries (15). Specialized Corporation presently markets a tri-spoke carbon fiber, Kevlar Aramid and glass composite rim which was aerodynamically designed using a super computer (21).

Rims can also be made aerodynamic by utilizing a high flange and a narrow profile. Care must be taken to ensure that the tire and the rim interface smoothly to decrease turbulence due to discontinuity. High flange rims help to improve wheel stiffness (7,13). The true aerodynamics of wheel design are not well understood; wind tunnel testing is needed at speeds and conditions similar to those encountered during racing (15).

Push-rings, attached directly to the spokes via stand-offs, are usually between 12 and 18 inches in diameter. Larger diameter rings allow faster acceleration but may decrease peak speeds (3).

The rear wheels can be mounted rigidly or with quick-release axles. Rigid threaded mounts provide a stiffer fit (7,13). Mounting the wheels with camber gives the chair a larger footprint, increasing its stability. Camber also permits a more natural push motion straight down from the shoulders (20). Too much camber often stresses the spokes and decreases wheel rigidity (3). A camber of about 10° is preferred by most users but varies between individuals from around 2° to as much as 12° (4). Alignment of the wheels is also critical. Tires that toe-in or out increase road friction (13,14,20). Misalignment due to repeated rim removal, frame settling, or abuse during a race is common. For these reasons, procedures to correct alignment should be as simple as possible. One method uses spacers to torque the frame into alignment (11). Kushall developed a method in sports chairs which uses a rotating shaft for alignment. Other manufacturers use a mounting plate that can be shimmed to the desired camber and alignment.

Using only one front wheel helps reduce rolling resistance and chair weight, but makes the chair less

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stable (13,17). Using larger tires (35–50 cm) in place of small casters helps avoid front wheel flutter, spreads the weight out more evenly, and allows for easier steering methods (7,19). However, a small front wheel can reduce the chair's aerodynamic drag (15). Front wheels can be mounted using a fork or a cantilever-type design.

Steering mechanisms require some trail. Trail helps eliminate flutter and makes the steering system stable (13). Steering mechanisms and compensators are used to allow propulsion through corners and adjust for road crown (22), allowing the user to concentrate on propulsion.

Aerodynamics. Wind resistance "drag" is caused by both normal and tangential (skin friction) forces whenever a body moves through the air. The flow of air over each individual part of the system is influenced by the flow over the rest of the system.

Aerodynamic drag is expressed by:

$$\text{Drag Force} = \frac{C_d \, \rho_{air} v^2 A}{2 \, g}$$

where C_d = drag coefficient
ρ_{air} = density of air
v = air velocity
A = frontal area
g = gravitational constant

The power consumed in overcoming this force during motion is:

$$\text{Power} = \text{Drag force} \times v$$

Therefore, the power to overcome wind drag is proportional to the cube of the velocity of the vehicle (23). Obviously, this can become a determining factor in racing competition. As an example: over 80 percent of the energy to propel a bicycle at 20 miles an hour goes toward moving 1,000 pounds of air out of the way every minute (24). Since air density and gravity are uncontrollable, there are two ways to maximize velocity by minimizing the drag force: 1) by reducing the frontal area, or 2) by reducing the drag coefficient. The drag is a function of the shape and surface finish of the human/vehicle system. The shape and surface finish control how the air passes over the system. Three possible types of air flow are associated with drag: laminar flow, which governs when the vehicle shape makes gradual transitions, and the surface is smooth so that the air can flow smoothly with low drag; turbulent flow, caused by sharp transitions or rough surfaces, which makes the air eddy over the surface, producing much higher drag; and separated flow, caused by sharp transitions that eddy the air in large swirls, which causes less drag than turbulent flow. Separation is more likely to occur from laminar upstream flow than from turbulent flow (23). With this in mind, the shape of the human/chair system should be designed with smooth transitions, a smooth finish, and the smallest frontal area possible.

Smooth transitions and finish should be part of the design criteria for the frame, keeping in mind how the user fits into the flow path. Frontal area is best minimized by altering the position of the pilot, taking careful note of how the frame fits around him/her. Other considerations, such as helmet shape and material, water bottle position, and frame material can also be used to help reduce drag (24).

Ergonomics. Ergonomics is the science of optimizing human work conditions with respect to human capabilities. Some major areas addressed by ergonomics include health, safety, comfort, and efficiency (20).

The interface between chair and user needs more research. Quantification of variables and performance parameters for this biomechanical system can provide the most useful results (7,8,25). Though some quantifying work has been done, much more is needed (5,6,8,11,12,16,18,19,20,22, 25,26). Some quantified test results have shown how efficiency and speed are related to stroke length and race length, elbow position, and optimal push-ring diameter.

The major problem so far is that each chair must be custom-fitted to each user. Many race chairs are individually hand-crafted (7,13). No interpretable data has been collected that can relate the importance of anthropometric and other physical body measurements to chair dimensions and performance. Because of this lack of data, it is uncertain which parameters are important. Relationships between chair dimensions, chair controller locations, body dimensions, range of motion, physiological efficiency, and system performance all need to be researched. Quantitative results are not only much more readily interpretable, but also permit mathematical modeling, simulation, and computer analysis of the human/chair system.

Materials. Most current racing chairs are made of high-strength, low-density metals, such as chromium molybdenum alloy steel (chromoly), titanium,

or aluminum alloy. These provide the needed strength, stiffness, and low weight desired for racing chairs. For small-scale projects, chromoly has the advantage of low material and manufacturing costs. Though composite materials have the desired properties for racing chair design, there have been few attempts to use them. Composites have seen extensive use in many other sports and for high-performance equipment such as fishing poles, golf clubs, tennis rackets, skis, bikes, boats, planes, and race cars (27,28,29). For several reasons, the entry of composites into the field of racing chair design has been slow. High-tech composites are fairly new, being developed only about 20 years ago (29). A widespread understanding of their uses and limitations is just now becoming a reality. Also, composite materials are still more expensive for manufacturing purposes than are metals, though they are becoming more competitive (30).

There are many advantages to using composites. Composite structures can be stronger and stiffer than steel and aluminum at a fraction of the weight. They show superior impact resistance and dissipate less energy into vibration. They can be contoured to almost any desired shape, using fewer joints and with less wasted material (28).

There are many different types of composites. Three general categories are particulate, laminar, and fiber. Laminated fiber composites provide the necessary physical attributes for racing chair design. Laminated composites consist of layers of fibers in predesignated orientations imbedded in a resin matrix. The matrix provides ductility and toughness. The fibers add strength and stiffness while keeping the weight down. A strong bond between the matrix and the fibers must exist to preserve the beneficial qualities of each component (31).

Many different materials can be used for the fibers. The strength of the fiber depends on its material and diameter (31). Carbon or graphite offer the best characteristics for race chair design. Their high stiffness with low density provide the best mix of properties, though the cost is higher. Cost, strength, and stiffness trade-offs must be dealt with (30). Also, graphite can be laid-up (i.e., placing resin-impregnated cloth made of composite fibers on the mold and/or over preceding layers) by hand, unlike many other composites (27). Often a foam core is used with the composite lay-up on the outer surfaces. This "sandwich" construction increases the cross-sectional inertia of the lay-up, reducing the bending stresses while maintaining the weight and tensile strength properties of the material (30,31).

The amount of fiber to be used and its direction of lay must be determined. Many weights and weaves of fiber are possible, each with different working properties. The term "tow" is used to describe the direction which has the most strands of filaments running parallel. Warp is the direction of the fibers used to hold the tow strands in place. The different types of weave determine the drapability, cost, wetability, and stiffness of the cloth (30). Two major categories of tow and warp combinations are commonly used for hand lay-ups: unidirectional and bidirectional. Unidirectional composites consist mostly of tow fibers with just enough warp to hold them in place. Bidirectional composites have an even mix of tow and warp fibers, creating more cloth-like material. A proper understanding of composite lay-up technique can allow passive tailoring to create an end material with the desired bending and torsion coupling, taking full advantage of the material's anisotropic behavior (28).

Determining how much material and what directional strength is required is not an easy task. Careful planning of the lay-up order and direction can result in a superior strength-to-weight ratio material. Simple isotropic material theories cannot be used with composites. Thermal stresses, residual stresses, hydrothermal factors, and load stresses and strains must all be considered.

This increased number of variables requires special attention. Some work has been done to fit nonlinear composite data to statistical curves. Other theories show some correlation between properties such as density, conductivity, and Young's modulus to a mixture ratio (31). Many times, the increased difficulty in analyzing anisotropic materials has lead designers to default to using quasi-isotropic lay-ups that can be analyzed and laid-up more easily. The drawback is over-engineering the material strength required in some directions, resulting in a slightly heavier design.

The most effective analytical methods require the use of computers. Computers can be used to do both micro- and macro-mechanical analysis of the design to determine the required ply strength and stacking order. Stiffness characteristics can be estimated using laminated plate theory, and strengths using modified quadratic failure criteria. These

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techniques must be judiciously applied in areas such as joints or near holes. Use of finite element analysis (FEA) and simulation softwares can determine the load needed to create "first ply failure," for complex-shaped designs (29).

When the analysis has been completed, construction may begin. Hand lay-up techniques are good for working on prototypes. Many publications offer guidance on these techniques, giving suggestions on the order in which plies should be laid, how to get superior wetting (i.e., impregnating the composite cloth/yarn with resin) without getting air bubbles, how to avoid irritation from the epoxy, and much more. One point, unanimously stressed, was that the most importantant step in doing a composite lay-up is preparation (27,28,30,32).

METHODS

Creating the Shape of the Frame

The importance of a favorable aerodynamic shape was discussed during the literature review. Air drag is reduced by decreasing frontal area and streamlining the contours of the chair pilot system. NWAA rules state that no items may be added to a chair strictly for the purpose of creating aerodynamic advantage. This has been interpreted in several cases to mean that nonstructural components which serve primarily to reduce wind resistance are unacceptable. A common test used is: if the chair still functions with the aerodynamic components removed, those components are disallowed. Some racers currently use strapping and seat buckets which serve to reduce aerodynamic drag as well as provide support. For this reason, design features must demonstrate primary structural and/or safety benefits; any accrued aerodynamic improvement must be secondary. Thus, a space frame being completely structural might incidentally provide much better contouring aerodynamically than a strut-chassis-type frame.

Determining the Best Shape. Not only should the shape be streamlined, it must also be fit to the pilot's position. To accomplish a prototype design, profile photos were superimposed, in both the up and down positions, with the pilot in his current racing chair. The rear wheel axle was designed to be in the same position with respect to the seat, to allow the stroke motions to be the same. The front and rear wheel diameters were chosen by the pilot to be 16 and 26 inches, respectively. These sizes were chosen to create the desired power gear ratio, while simultaneously decreasing rolling resistance. The aim was to have the frame profile provide minimal aerodynamic drag for the rider in either the up or down position. Using results from the profile layout, clay models of potential chair designs were made. Width dimensions in the cockpit were determined using dimensions of the pilot. The nose width was designed to accommodate the front wheel while allowing for approximately 15° of steering angle with a 6 cm cantilever trail arm.

The frame was molded to partially shroud the rear wheels with 10.75° of camber. The shrouding primarily serves to protect the pilot's arms during propulsion and is common practice for racing wheelchairs. Models varied in attack angle of the contoured nose and rear wheel shrouds. Wheel guards can improve the streamlining of the frame while improving safety by helping to keep the pilot's arms from contacting the spinning tires.

Wind Tunnel Testing. Two scale models were made of plaster of paris. These models were smoothed, painted, and fitted with wheels and a rider model. Model A had a narrow nose, guards over the wheels, and a steep front-end attack angle. Model B had a slightly wider, round nose, no wheel guards, and a more gradual front-end angle of attack. The model rider, made of soft clay, was mounted in race position. Soft clay was used to simulate the skin and clothing of a real racer. These models were wind tunnel tested with a stationary ground surface. Drag force was measured in the direction opposite the wind flow. Drag forces for each model were recorded at wind speeds from 3,000 to 9,000 feet per minute at 1,000 foot per minute intervals. Because similitude requires the model and the actual system to have the same Reynolds number, and these wind speeds are slightly low for a one-ninth scale model to exactly simulate the behavior of a full-size chair under normal conditions, the results proved to be worthwhile (**Table 1** and **Figure 1**). The results showed the drag force to be proportional to the square of the velocity, as expected. The models with a rider in place showed almost twice as much drag as their pilotless counterparts. Interestingly, model B with its wider nose and no wheel hubs showed slightly less overall drag than the narrow-nosed model. A 2×2 analysis of variance

Table 1.
Wind tunnel model results.

Air Speed (m/s)	Drag Force (grams) Model A w/Pilot	Model B w/Pilot	Model A w/o Pilot	Model B w/o Pilot
15.24	46	43	27	26
20.32	78	75	46	44
25.40	110	112	65	65
30.48	155	161	82	88
35.56	205	215	112	120
40.64	260	275	132	137
45.21	340	360	192	188

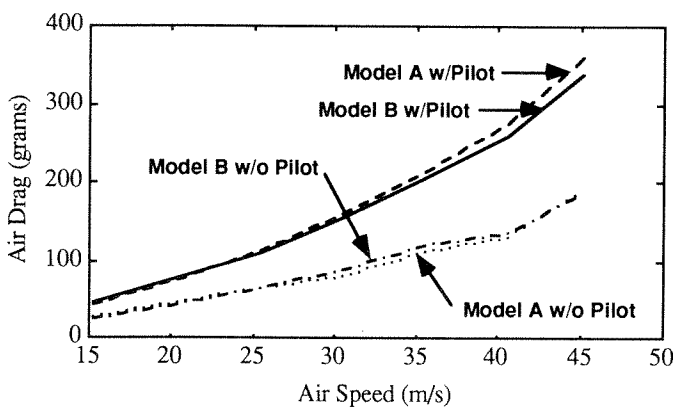

Figure 1.
Wind tunnel results for composite racing wheelchair models.

(ANOVA) showed the effect of the pilot on air drag to be significant ($p=0.024$), and the difference between the aerodynamic drag of models A and B not to be significant ($p>0.05$). The interaction was also not significant ($p>0.05$). Also of importance but not apparent from the data in **Table 1** was the stability of the shapes. Even though model B showed less overall drag, it experienced more lateral oscillation during testing than model A. Reaching a definitive, conclusive decision from this observation is difficult. The increased oscillation of the first model may be attributed to the sharp transition over the unhubbed rear wheels. Even a slight misalignment of one of the rear wheels could excite oscillations. The lower drag was probably due to the rounder nose and smoother attack angle of the front end. From these observations, the final chair shape was designed to incorporate a slightly rounder nose, a gradual attack angle, and guards over the rear wheels (**Figure 2**).

Determining the Frame Structure

There is always a trade-off between strength and weight in any structural design. Carbon graphite fibers can increase the strength-to-weight ratio. Correctly identifying high stress areas allows the strength-to-weight ratio to be optimized. FEA was used to determine the frame contour. FEA uses a computer model in which the frame is represented by many small elementary units or "elements." Each element is defined by a shape function: an equation that models the shape of the element. Stresses and displacements across elements can be estimated by minimizing the potential energy equation for all elements simultaneously. Because of computational complexity, software packages must be used to determine an optimal solution. The FEA package ALGOR was chosen to solve this project's finite element model. Like most FEA software packages, ALGOR optimizes the order of solution using complex analysis methods that account for shear, tensile, and compressive loads. It can display the results in many different ways. The solution's accuracy depends on the placement, size, and shape of the modeling elements. Areas with a high stress gradient require more elements to give the same degree of accuracy as regions where the stresses vary more gradually. Some initial assumptions about where the high stress areas might be located must be

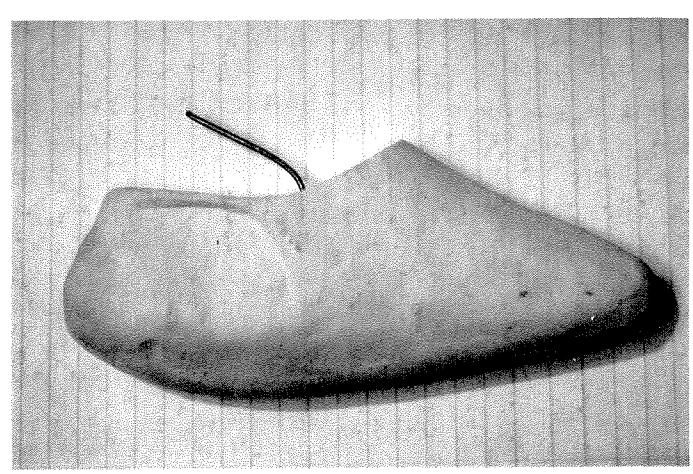

Figure 2.
Clay model of the aerodynamic composite racing wheelchair space frame.

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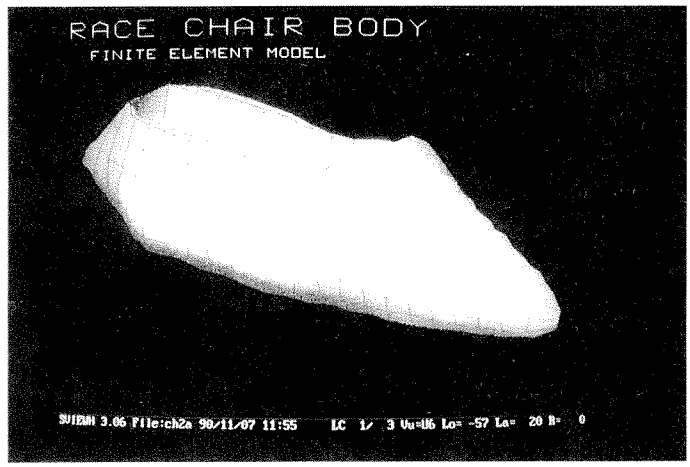
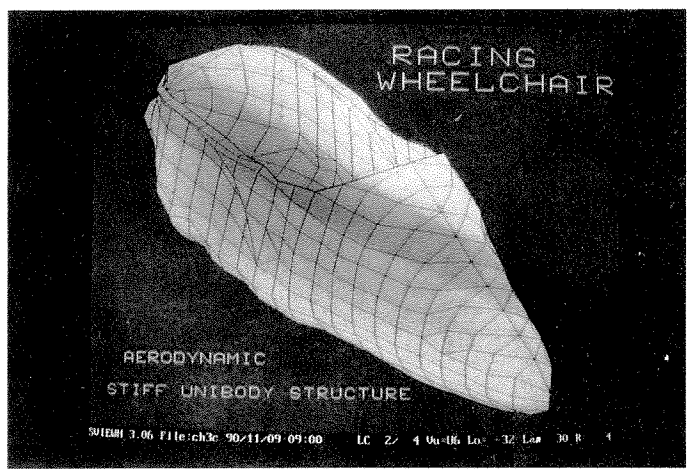
made before the FEA model is created. More elements are then placed in anticipated high stress areas. It was assumed that stress would be higher near points where loads were to be applied. Therefore, more elements were placed near wheel, seat, and steering mounts. The results of FEA are sensitive to element shape. The frame, much wider and longer than it is thick, can readily be modeled as a (curved) two-dimensional thin plate. Either three- (triangular) or four- (quadrilateral) sided elements can be used. Triangular elements appear stiffer under FEA than do quadrilateral elements; thus, mixing element types should be avoided.

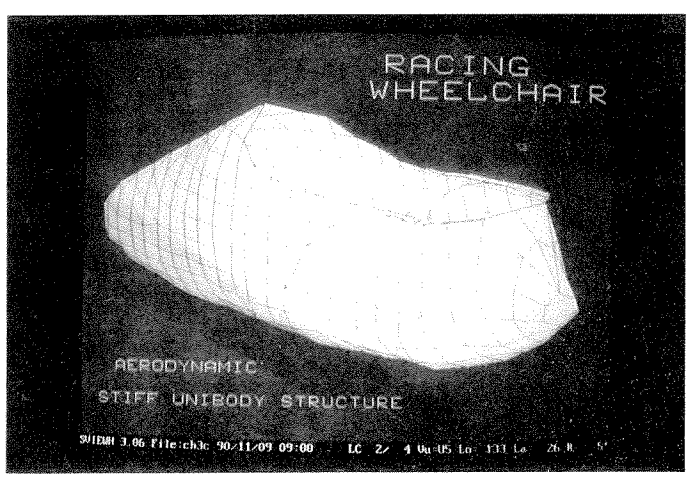
Developing the Model. A computer model was based on the more aerodynamically shaped clay model (**Figure 3a, b, c**). A reference line was scored down the length of the clay model; a similar line was placed on the profile drawing. The line on the profile drawing was used to determine the angular orientation of the frame in space and relative to wheel positions. Cross-sections were sliced perpendicular to the scored line from the tip to the tail of the model. The width of each cross-section was 7.5 mm to preserve the shape of the model and create sufficient elements. These cross-sections were traced onto grid paper. For each cross-sectional slice, points chosen along its contour defined the curve. Extra points were placed in areas where high stresses were expected. Horizontal and vertical positions of all points were recorded along with slice depth to create x, y, and z coordinates for each point. The y and z coordinates were then plotted back onto grid paper. This insured that the model shape had been preserved and allowed for lines to be drawn in to connect the points. These lines created the edges of the elements of the FEA model. The elements were configured as quadrilaterals whenever the frame geometry allowed; otherwise, triangular elements were created. Once a satisfactory shape was determined, all three coordinates were multiplied by nine to return the dimensions to the full-scale coordinates used to develop the model on ALGOR. The points were connected with lines as had been done before by hand. The model was rotated back to its world position as calculated by the profile drawing and the score line. The resulting FEA model consisted of 411 points, 844 lines, for a total of 435 elements. Before any FEA results can be attained, material properties must be specified for the elements, and the loads must be assigned to the model. Additional nodes



(a)



(b)



(c)

Figures 3a,b,c.
Computer finite element model of aerodynamic composite racing wheelchair space frame.

were added to areas which showed high levels of strain. The analysis was then repeated with the modified mesh.

Modeling Material Properties. Material properties were determined by testing specimens made of quasi-isotropic carbon fiber and of a quasi-isotropic carbon fiber and glass mix. These materials were chosen because of their good drapability and wetability (18,27). Load and strain data collected for these specimens led to the results shown in **Figure 4a** and **Figure 4b**. The glass did not add any strength to the material, only bulk, but it did give a better finish which would be less abrasive to the pilot, being less susceptible to environmental wear. Peculiar units of measurement are required to allow ALGOR, which was designed to use English units, to process the FEA model, which was formulated in metric units.

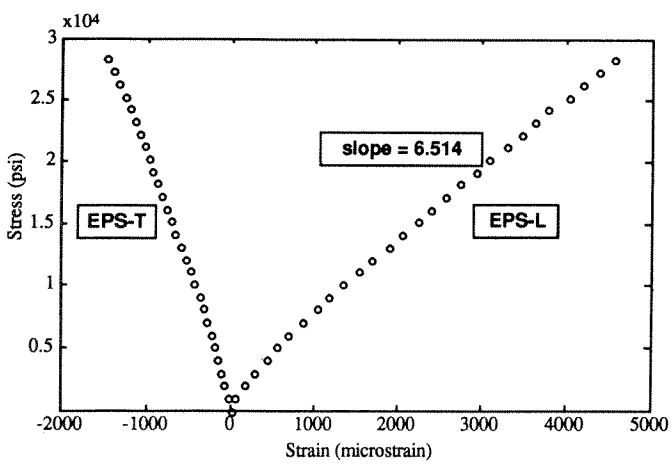


Figure 4a.
Stress and strain data for carbon fiber test specimens.

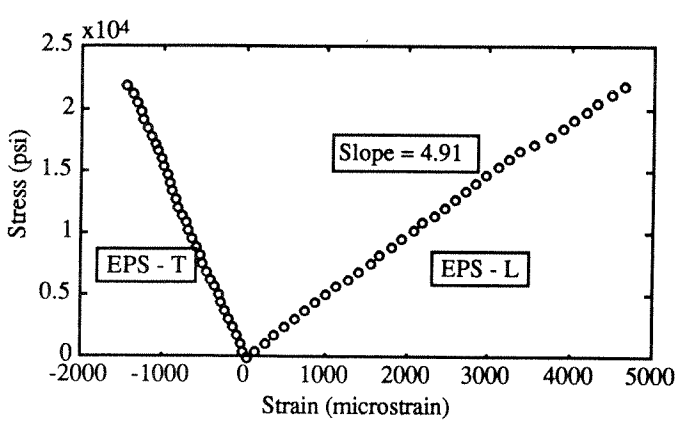


Figure 4b.
Stress and strain data for carbon fiber-glass test specimens.

Ultimate strength = 2,000 kg/cm^2 (28 ksi), Young's modulus = 458,000 kg/cm^2 (6,5000 ksi), Poisson's ratio = 0.325. These results concur sufficiently with those published. Similar materials such as T300, AS, and IM6 composites have Young's moduli of 10.10, 7.95, and 11.36 msi, and Poisson's ratios of 0.30, 0.28, and 0.30, respectively (29). Our first FEA models employed elements with the properties of one layer of quasi-isotropic carbon fiber. From the results of the one-layer models, areas that required strengthening were located. These areas were strengthened by multiplying the thickness of the elements by some multiple of a single layer or by adding core material to the center of the quasi-isotropic lay-up. Since the tensile strength was already adequate for the in-plane loads, foam provided a good core material to improve the bending stiffness without adding weight. For cored areas, the properties can be estimated by noting that Poisson's ratio does not change when a core is added. Young's modulus can be estimated using the primary flexural modulus of the composite lay-up.

The primary flexural modulus is determined by first integrating over the thickness of the composite defined by its ply stiffness matrix Q.

$$[Q] = \begin{bmatrix} \frac{E}{1-\upsilon^2} & \frac{\upsilon E}{1-\upsilon^2} & 0 \\ \frac{\upsilon E}{1-\upsilon^2} & \frac{E}{1-\upsilon^2} & 0 \\ 0 & 0 & \frac{E}{2(1+\upsilon)} \end{bmatrix}$$

Where E = Young's Modulus
υ = Poisson's Ratio

The flexural stiffness, D, becomes

$$[D] = 2\int_{z_c}^{\frac{h}{2}} [Q]\, z^2 dz$$

Where h = the laminate thickness
z_c = the top face of the core

$$D_{ij} = (\tfrac{2}{3})Q_{ij}[(h/2)^3 - (c/2)^3]$$

Where c = the core thickness

The primary flexural modulus, E_{flex}, can be determined by first normalizing the moment of inertia matrix:

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$$[D^*] = \frac{12[D]}{h^3}$$

and then finding its inverse matrix

$$[d^*] = [D^*]^{-1}$$

whose major element is d_{11}^*.

$$E_{flex} = \frac{1}{d^*_{11}}$$

Loading the Model. A number of cases of frame loading were chosen to mimic loads that a race chair might experience in a race. Loading points were determined from the grid drawings. Six points were used to mount the seating system; four points were used to mount the three wheels and a compensator (**Figure 5**). The position of the compensator mount was determined geometrically. A 22-cm lightweight stainless steel push-pull compensator was manufactured. On a top view of the front of the frame, drawn using the coordinates of the FEA model, the position of the front wheel was drawn with a 6 cm cantilever trail arm. The size of the moment arm created by this mounting scheme can be determined from the drawing. Three load cases were designed to model possible pilot positions, and four load cases were used to model possible road shocks.

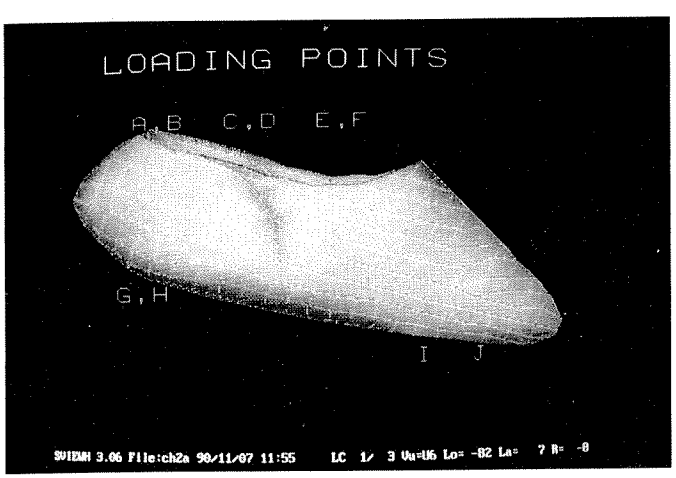

Figure 5.
Loading points for finite element analysis. 'A' and 'B' are the right and left rear seat mounts; 'C' and 'D' are the right and left center seat mounts; 'E' and 'F' are the right and left front seat mounts; 'G' and 'H' are the right and left rear wheel mounts; 'I' is the compensator mount; and 'J' is the front wheel mount.

In **Figure 5**, 'A' and 'B' are the right and left rear seat mounts; 'C' and 'D' are the right and left center seat mounts; 'E' and 'F' are the right and left front seat mounts; 'G' and 'H' are the right and left rear wheel mounts; 'I' is the compensator mount; and 'J' is the front wheel mount. Pilot loads were estimated using a 70 kg pilot distributed over six seat mounts while holding the wheel mounts fixed. The seat mounts protrude inward with an estimated moment length of 1 cm. Three load cases were used: loads distributed toward the rear seat mount, loads equally distributed over the seat mounts, and loads distributed toward the front seat mount. The pilot loads were all in the back third of the wheelbase. Road loads, applied while fixing seat mounts, were determined using the forces resulting from the worst-case pilot position during seating loads. Front wheel impact loads were determined for the pilot in the forwardmost position; rear wheel loads were those for the pilot in the rearmost position. Loads were also applied to the compensator mount to mimic jarring of the front wheel in either direction. The compensator spring constant was determined to be 80 lbs/in. Moments for the front wheel were determined using the frame geometry, and moments for the rear wheels were determined knowing the camber, wheel radius, and an estimated typical mounting distance. For all load cases, these static forces were multiplied by three to allow for the effects of dynamic loading (31).

Initial Model Findings and Improvements. Each FEA solution for the loaded model required simultaneous reduction of 2,443 equations. Areas requiring strengthening were identified by using the results from the single thickness model. Areas with deflections exceeding one-hundredth mm, or with stresses exceeding one-third the ultimate strength of the material were strengthened. A safety factor of three was applied to account for the effects of fatigue and possible unexpected loadings (**Figure 6a** and **Figure 6b**). With only a single quasi-isotropic carbon fiber layer, stresses at some points on the frame exceeded four times the ultimate strength of the material. The high stress areas were divided into those that exceeded the ultimate strength and those that exceeded one-third of the ultimate strength. The small areas with the highest stresses, such as wheel mounting sites, were enhanced with a 1-inch core. High stresses near the cockpit were enhanced with a half-inch core. Other high stress areas were strength-

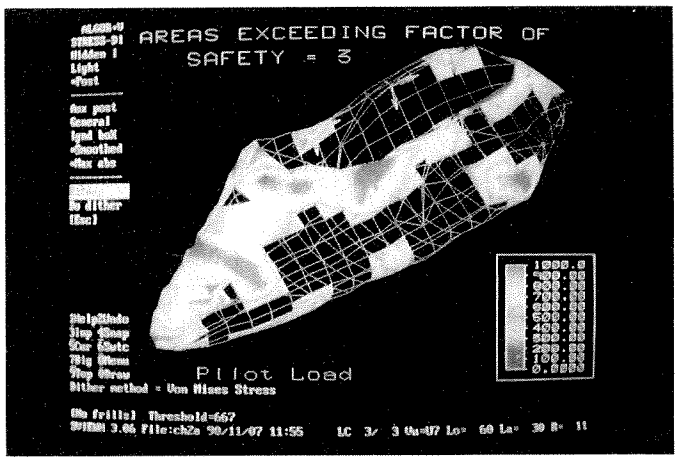

Figure 6a.
Areas exceeding safety factor of three for single isotropic layer with pilot loads.

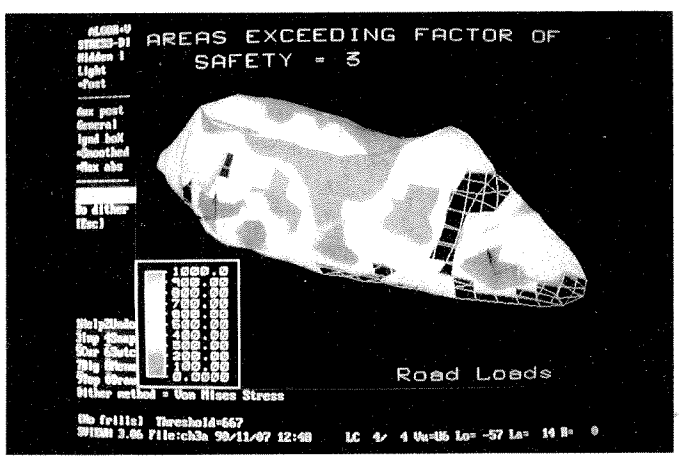

Figure 6b.
Areas exceeding safety factor of three for single isotropic layer with road loads.

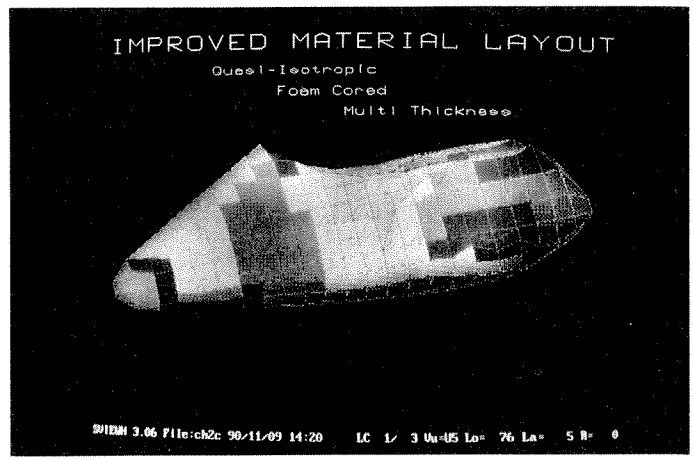

Figure 7a.
Material layout for quasi-isotropic cored body (left side).

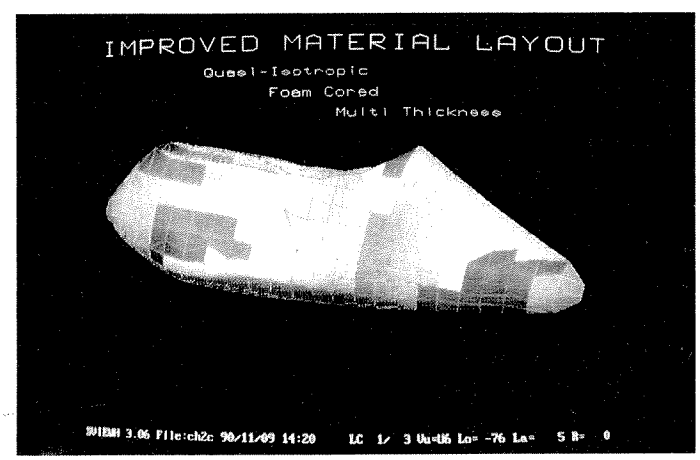

Figure 7b.
Material layout for quasi-isotropic cored body (right side).

ened with quarter-inch core material. Double thickness quasi-isotropic carbon fiber was used in transition to the lower stress areas. The final material lay-out may be seen in **Figure 7a** and **Figure 7b**. The properties for the cored areas were estimated using the flexural modulus as previously described. This combination of decreased modulus with an increased thickness resulted in improved strength; a result typical of flexural estimation.

Improved Model Results. **Figures 8a, 8b,** and **8c** and **Figures 9a** and **9b** show stress contours of the reinforced model in the pilot and road load cases, respectively. Results from the modified model met the stress and deflection requirements. The stress scale on the improved material model was different from that used with the single thickness layer of material. The cored FEA models are shown on a scale of 0–400 kg/cm^2, while the single-layer models were displayed on a scale of 0–1,000 kg/cm^2. The highest stress level found for the improved model in any of the loadings was only 635 kg/cm (almost 15 times less stress than in the original model). Locations of high stress areas from road loads are almost opposite the position of high stress areas from the pilot loads. This could help avert any failure due to combinations of loading.

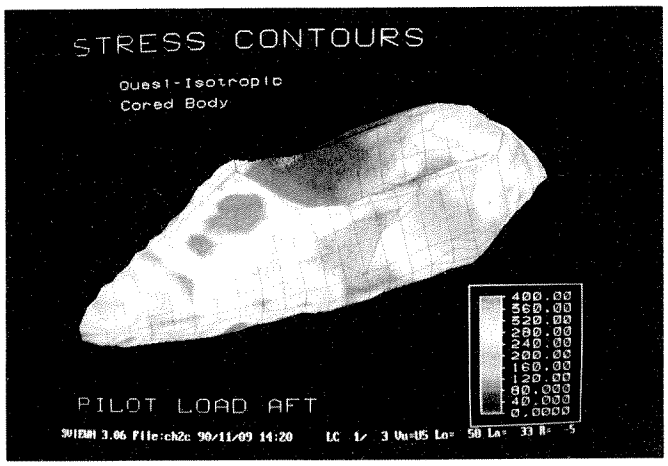

Figure 8a.
Stress contours for quasi-isotropic cored body: pilot load aft.

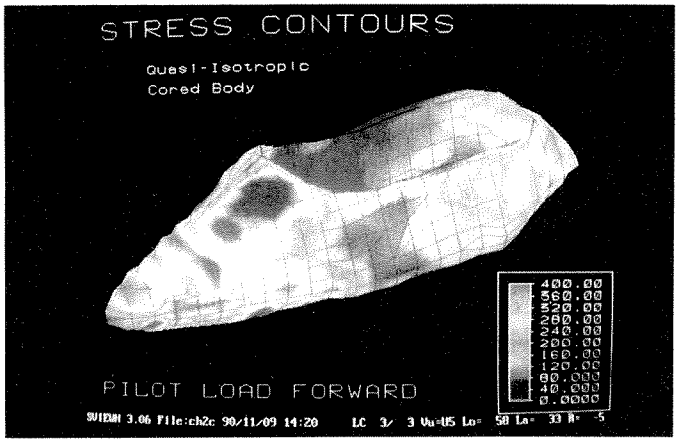

Figure 8c.
Stress contours for quasi-isotropic cored body: pilot load forward.

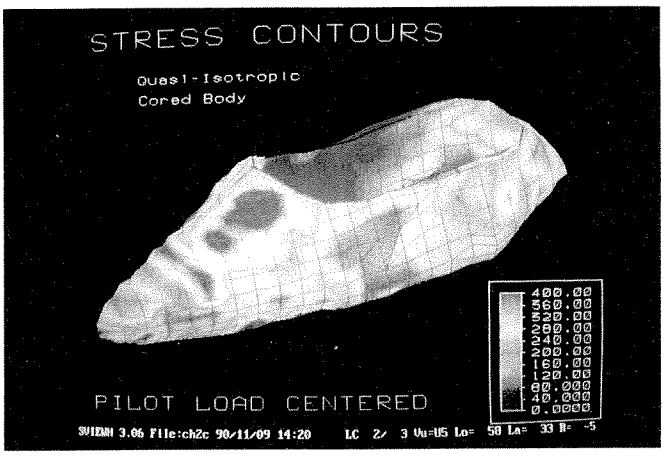

Figure 8b.
Stress contours for quasi-isotropic cored body: pilot load centered.

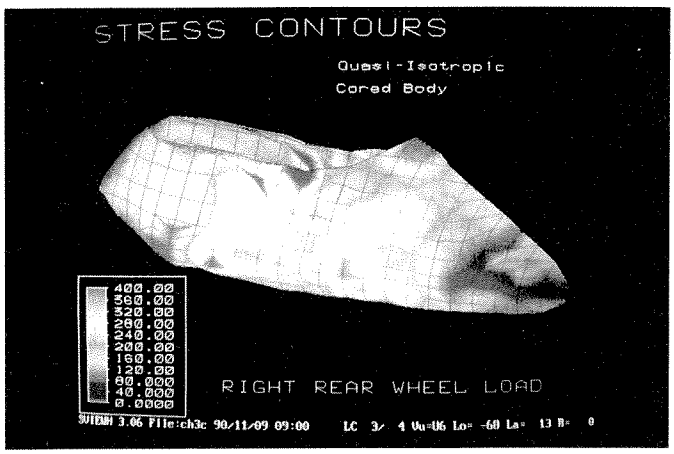

Figure 9a.
Stress contours for quasi-isotropic cored body: road load right rear wheel.

RESULTS

Building a Prototype

Building the prototype required creating a mold. When the lay-up was completed, the frame was seamed and trimmed. Next, the wheel and steering mounts and seat were attached to the frame. Finally, the wheels were aligned.

Building the Frame. Full-size patterns of the right and left halves of the chair were cut using cross-sectional data. These patterns were traced onto Styrofoam™ and cut using a hot wire. Cross-sectional widths, cut with a band saw, were glued together to form right and left halves of the chair. The two halves were sanded to smooth the surface contour. Sanding was also used to recess core material. The molds were covered with plastic wrap using double-stick tape to prepare them for lay-up. (The plastic wrap protects the foam from the resin and makes the finished shell easier to release.) A large aluminum sheet sprayed with mold-release was used as a work table. The carbon fiber was cut directionally to allow enough pieces to create a quasi-isotropic lay-up for each mold half. Some pieces required seams to cover the entire mold. No

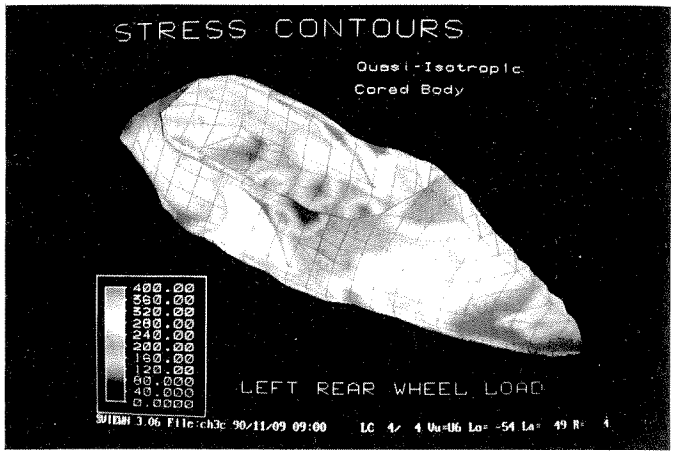

Figure 9b.
Stress contours for quasi-isotropic cored body: road load left rear wheel.

seams were placed directly over other seams to eliminate stress risers created by increased thickness at the seam (30). The two frame halves were molded by using standard hand lay-up procedures. The foam cores were puttied in the center of the lay-up using a microbubble slurry. A flange, left at the edge of the mold on the aluminum, helped to insure the lay-up's integrity at the edges and to create an easy way to match molded halves. Fiberglass was used for the outermost layer. After 2 days the molds were released and trimmed. The two halves were matched and bolted together along the flange. Seat and front wheel holes were cut, and the inside seam was sanded rough. Using long strips of carbon fiber, the inner half of a quasi-isotropic seam was created. When the seam dried, the outer flange was removed. The outer seam area was then sanded rough to create a bonding surface and the second half of the quasi-isotropic seam laid. Some extra material was laid-up around wheel and cockpit openings to increase their strength, and fiberglass was placed in areas that might contact the pilot. The rough frame and seat are shown in **Figure 10**.

Attaching Wheel and Steering Mounts. Click Studs (Click Studs, Bergdahl Associates, Inc., Reno, NV), were used to mount the wheels and steering mechanisms because they do not require drilling holes that may degrade the integrity of the frame material. The studs are surface-mounted using an epoxy cement. When properly adhered to a graphite substrate, each 1.25-inch mounting base can support 550 lb in tension of 1300 lb in shear. Used in the fashion proposed in the models, most of the load is expected to be in shear. The front and rear wheels mount to faceplates, which attach to the Click Studs. The compensator mounts directly to a stainless steel stud, slightly larger than a Click Stud, which had a face better suited for tightening. The wheel mounting plates were machined from aluminum 7075, T6 because of its high strength-to-weight ratio.

The front wheel was mounted first and adjusted with spacers until it was vertical. The rear wheels were mounted and aligned using an alignment tool (11).

The Seating System. The pilot of the chair must be securely seated in the proper position in order to get the best foundation from which to drive the chair. Using a Pin Dot seat molding frame (Pin Dot Products, Niles, IL), a plaster mold was made of the pilot's back and seat in his racing position. The seat was laid-up by using the same technique as with the chair mold in **Figure 10**. Fiberglass was chosen for the lay-up material because it would be less irritating to the pilot. The seat was mounted to the chair frame using Click Studs. Two rails, also fastened onto Click Studs, allow adjustment of seat position.

Finishing. A smooth finish was needed in order to decrease aerodynamic drag and skin irritation. The body was sanded to remove any major discontinuities. The texture was then smoothed, as much as possible, using primer paint. Finally, a

Figure 10.
Rough lay-up of composite space frame and seat.

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gloss paint coat was applied. **Figure 11** shows the finished chair.

Expenses. **Table 2** gives a rough estimate of material costs required to build this prototype. These costs alone make this racing wheelchair expensive compared to contemporary tubular chassis designs. Labor costs would also be relatively high; however, costs could be reduced if the chair went into commercial production and materials were purchased in larger quantities. If performance was improved, there would still be interest by elite athletes, despite the high cost, since racing wheelchairs are special purpose vehicles.

Figure 11.
Completed composite space frame racing wheelchair.

Table 2.
Prototype budget.

Bidirectional Woven Graphite 42″ x .013″, 8HS Weave, 32 yds. @ $70.00 = $2,240.00	
Unidirectional Graphite 5″ x .006″, Plain Weave, 20 yds. @ $1.35 = $27.00	
Safe-T-Poxy Resin, 2 Gallons, $100.00	
Foam Cores and Microbubble Filler, $50.00	
Foam for Mold Shape, Styrofoam, $50.00 Molding	
Supplies:	
Paint Brushes, Rollers, Rubber Gloves, Wrap, Saw Blades, Contact Cement, Cleaners, $100.00	
Modeling Supplies: Clay, Plaster, Mold©It, Epoxy Glue, Paint, Sandpaper, Graph Paper, $40.00	
Photography Supplies: Film and Developing, $75.00	
Mounting Studs, Click Studs, $25.00	
Wheel Mounts, Steering Mount, and Compensator Material and Machining, $140.00	
TOTAL	$2847.00

Testing the Prototype

The new design was tested to measure its improvement over existing designs. The pilot has used the chair several times. The best testing, through repeated usage in a competitive situation, is yet to come. Several simple performance checks were possible, however.

At 32 pounds, the complete composite chair is nearly twice the weight of a typical race chair. The pilot noted that although the chair accelerated slowly, it handled well at road speeds. It is difficult to determine, without performing destructive testing, whether the unibody frame is actually stiffer than its strut-chassis counterparts. The chair has a very stiff ride. The pilot felt as if he had a firm base to transmit force to the push-rings. He reported that the rear wheel positions were slightly too wide for his preference and the seat was too far forward. The seat position was moved all the way back on the adjustable rails. The unibody design prevents moving the seat any farther back without altering structural integrity. The width, however, can be corrected with a simple modification of the wheel mounts. The unibody frame allowed the pilot to tuck in his arms when coasting, which improved the aerodynamics.

FUTURE IMPROVEMENTS

Positioning Improvements

In future designs, care should be taken to allow ample adjustment of seat position. With a unibody design this is critical. In this design, trying to contour the back of the frame too close to the pilot resulted in limitations on the seat movement.

Aerodynamic Improvements

The preliminary aerodynamic studies with the wind tunnel and plaster models could also have been improved. The wind tunnel did not account for ground motion and air viscosity effects. Only forces in the axial direction could be measured; lift and twist forces were not accessible. The models themselves were not exact. Spoked wheels were difficult to model, and the surface finish could only simulate that of the final chair. Increasing the number of

shapes and possible pilot positions would be useful. A better wind tunnel and improved modeling techniques might be able to determine the best helmet design and clothing material. Besides using an improved wind tunnel and models, better results might have been attained through FEA on a computer. Simulation may possibly offer a more accurate and cost-effective alternative.

Apart from possible modeling refinements, the manufacturing process could be improved to produce a more aerodynamic frame. The final surface of our frame was lumpy because of the imperfect fit of the core pieces. The easiest "fix" for this is to use a female mold instead of a male one. Then the smooth, aerodynamic shape would be preserved on the outside, and the lumpiness from the core would be on the inside. Measuring the frontal area using photos and a planimeter could, in the future, be a useful way to compare the aerodynamics of the prototype with more traditional chairs, giving frontal area values for quick comparison. This could be useful to future designs.

Structural Improvements

Though the FEA results helped optimize the structural strength, thus keeping the weight at a minimum, the final chair was still much heavier than desired. Perhaps this occurred because the shape of the chair and its strength were optimized separately. Optimizing them together might give a weight and drag compromise which would result in the best overall chair, one that would be better than either the best-shaped or lightest-structured chair. The weight problem could also be addressed by removing material. The initial structure was designed using a single layer of material. High stress areas were beefed up, but low stress areas were left alone. By using a finer weave material or leaving lightening holes, weight in the low stress areas could have been significantly reduced. Taking advantage of the nonhomogeneous properties of composites could greatly reduce the weight of the chair. Not every element requires the same strength in every direction (the back region of the frame is a possible candidate for redesign).

Because of the churning of the wheels and the nonaerodynamic shape of the pilot, the air flow in the back region is not laminar. Turbulent flow creates the largest drag. A sharp disturbance upstream in the structure can cause full-scale separation, lowering the overall drag force: material in the rear structure of the frame might be reduced so that only as much material remained as was needed to maintain the stiffness. This would be clarified during a more complete aerodynamic and structural optimization.

Integrating a seat base into the unibody frame would remove the need for any extra hardware that increases the system's weight. It is important to allow for full adjustability of seat position.

Frame weight might be further decreased by improving the lay-up technique. Because the core pieces did not fit perfectly, a slurry of resin and microbubble was used as filler. This filler was much heavier than the core material. The core reinforcement was 1 inch, 0.5 inch, and 0.25-inch-thick material. It is important that the transitions from one core thickness to another are continuous. Although the layout process would be more difficult, an exterior mold would make the exterior transitions smoother. Also, during hand lay-up, special care must be taken to insure that the material is completely impregnated with resin. This may have led to using excess resin in the material. Using a technique known as vacuum bagging, excess resin can be sucked out, leaving only the resin that is required.

Several Click Studs had to be replaced. Although the studs were strong, the epoxy adhesive had difficulty standing up to impact loads. Roughing up the bonding surfaces and increasing the mounting area might help to improve their strength.

More tests should be run on this chair to determine its strengths and limitations. The safety factor of three may be more conservative than was necessary. Some of the weight increase may turn out to be acceptable due to the decreased drag and increased frame stiffness. A kinematic analysis of the pilot may permit interface improvement.

DISCUSSION

The FEA model executed on a computer provided insight into structural problem areas in the design of unibody frame racing chairs. Slight modifications to the model can be used to investigate new shapes, loads, or materials without investing large amounts of time and money. With aerodynamic FEA software, the model could provide perspectives

on different improvements to reduce drag. Shape improvements may play an important role in reducing the racer's time during competition by helping to decrease drag for the user in either the upright or down position. Considering how much the air flow is deflected by current strut frames and that the frontal area increases around 30 percent in the up position, monocoque shapes should excel. Future work on unibody race chairs could start from this design and attempt to improve upon it by reducing the weight of the chair, to bring it in line with that of current strut-chassis chairs, or could try to show that the drag of the unibody chair compensates for its extra weight.

Although this composite chair weighs more than its competitors, the extra weight is compensated for in other ways (e.g., the lack of joints and other high stress areas in the unibody style might make the chair stiffer and safer).

It is important to remember that the race chair is only part of the system. The racer's weight, which varies significantly between individuals, also affects the ease with which the system can be propelled.

Other ways to improve the chair were discovered during construction: using a female, instead of a male, mold could improve the outer surface shape and texture; vacuum bagging excess resin could reduce the weight of the frame; and adhesive Click Studs provided an easy way to mount things to the frame without deteriorating the integrity of the frames structure (but stronger bonds should be sought out).

The molded seat made with the Pin Dot molding system turned out well. The seat provides the support and positioning needed to effectively propel the chair. These findings clearly indicate that the application of engineering technology can improve the design of the racing wheelchairs.

ACKNOWLEDGMENTS

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