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Borealis Structural Safety Report

University of Minnesota Solar Vehicle Project

March 20, 2001

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INTRODUCTION

Borealis, the University of Minnesota Solar Vehicle Project's American Solar Challenge entry, shares many of the design features of its successful predecessors, Aurora II, Aurora³, and Aurora 4. Chief among these is an emphasis on vehicle safety. The team began addressing safety concerns in the design conceptualization stage. Consequently, the Borealis design integrates safety concerns at all levels, and in most instances the driver is protected by a progressive set of safety measures. The result is a vehicle that is extremely safe, reliable, and competitive.

The following report highlights many of the safety considerations that went into the Borealis design. It is intended to address specific concerns outlined by American Solar Challenge rules, such as: driver cockpit penetration, frame materials and construction techniques, battery attachment and harness mounting points. The integrity of the related mechanical and electrical systems is also addressed. The team believes that avoiding a crash is the best way to survive. Also, there is an analysis and narration the logical progression of the most important crash loading situations. Finally, structural analysis is performed to verify the vehicle integrity in the loading situations required by the American Solar Challenge rules.

VEHICLE CONCEPT

The basic Borealis design includes two steerable front wheels and a single rear drive wheel with fully independent suspensions at each wheel. The vehicle layout positions the driver laterally along the centerline of the chassis and longitudinally slightly in front of the front axle line and in front of the rear axle line.

The batteries are placed in one enclosure in front of the drivers legs. The enclosure is sealed and electrically isolated from the driver and rest of the car, as required by American Solar Challenge regulations. The ballast is also mounted in front of the driver's legs.

The vehicle chassis includes a composite frame, suspension components, and a roll cage. In racing configuration it contains the driver, batteries, electric motor and controller, safety equipment and peak power trackers. The body is separate from the chassis and serves as the platform for the solar array. In racing configuration the body can be opened up like a peanut shell with the top half coming off and the bottom half staying connected to the chassis. The canopy area is removable to allow driver egress. The body is also easily removable to facilitate reorientation while in charging configuration. (See Figures 1 and 2)

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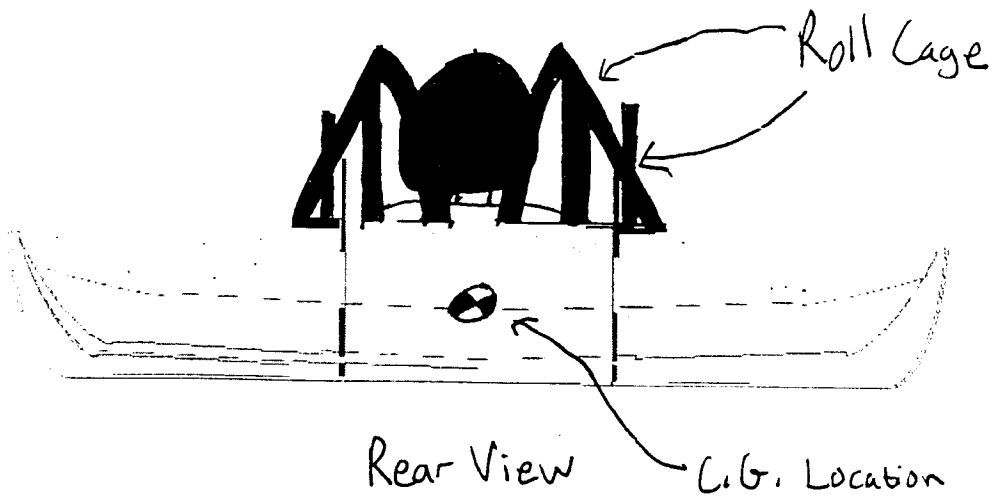
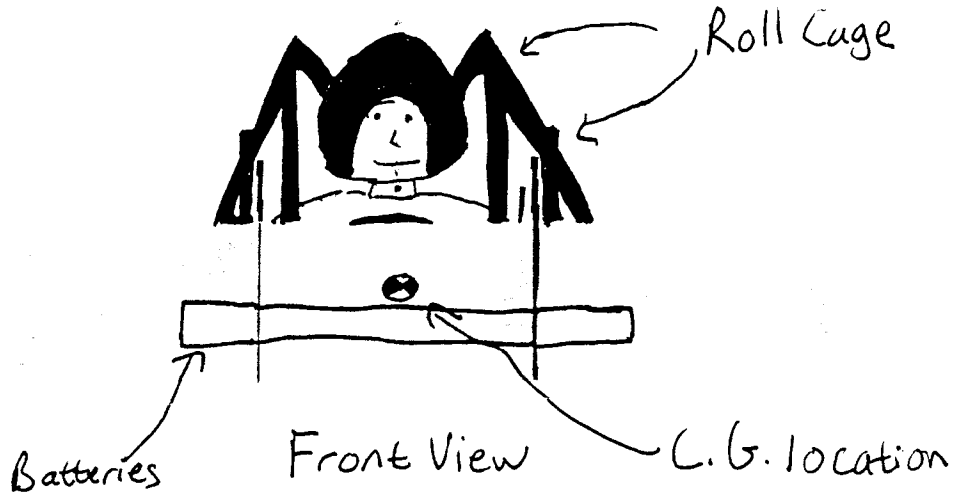


Figure 1. Chassis Detail

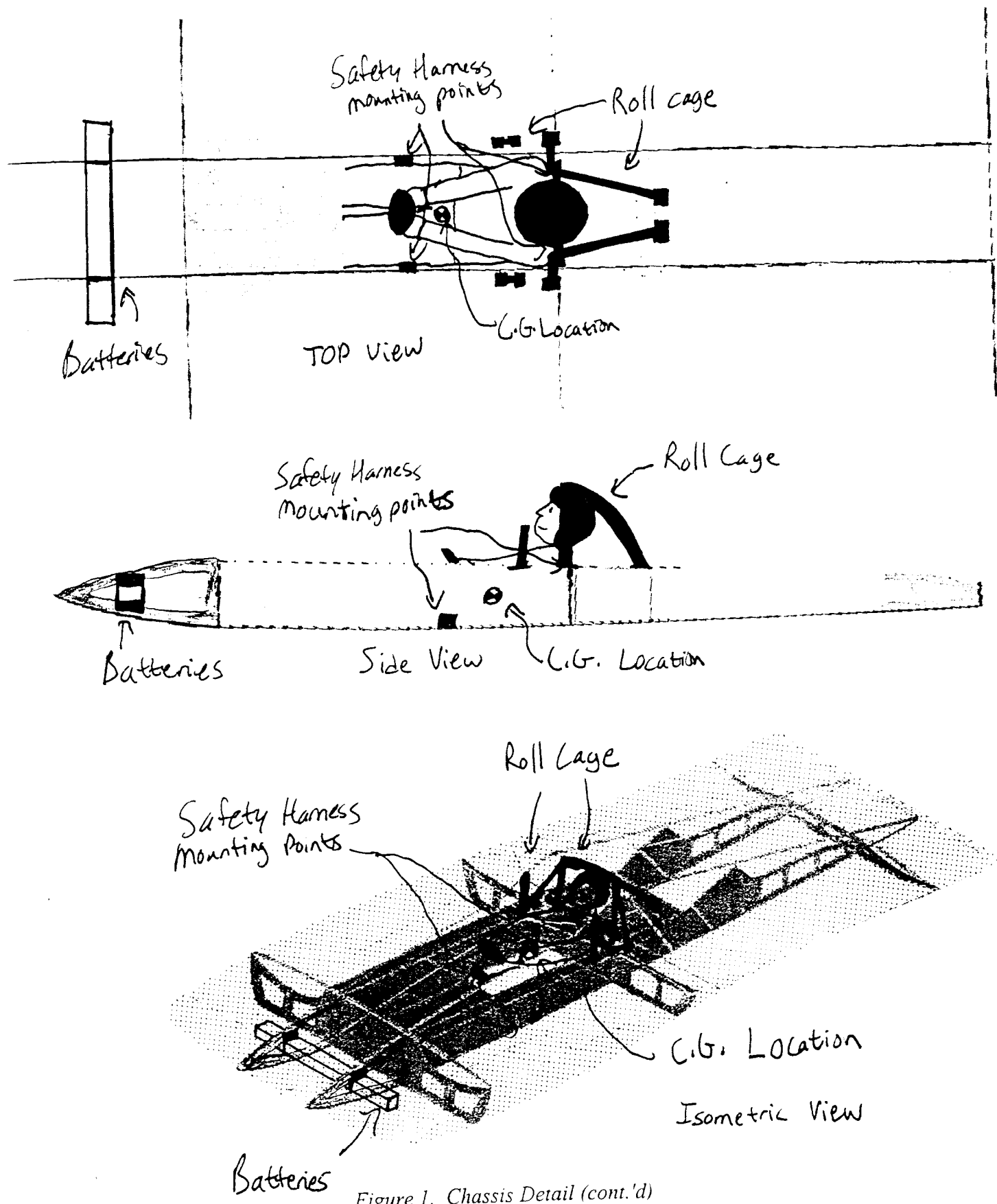


Figure 1. Chassis Detail (cont.'d)

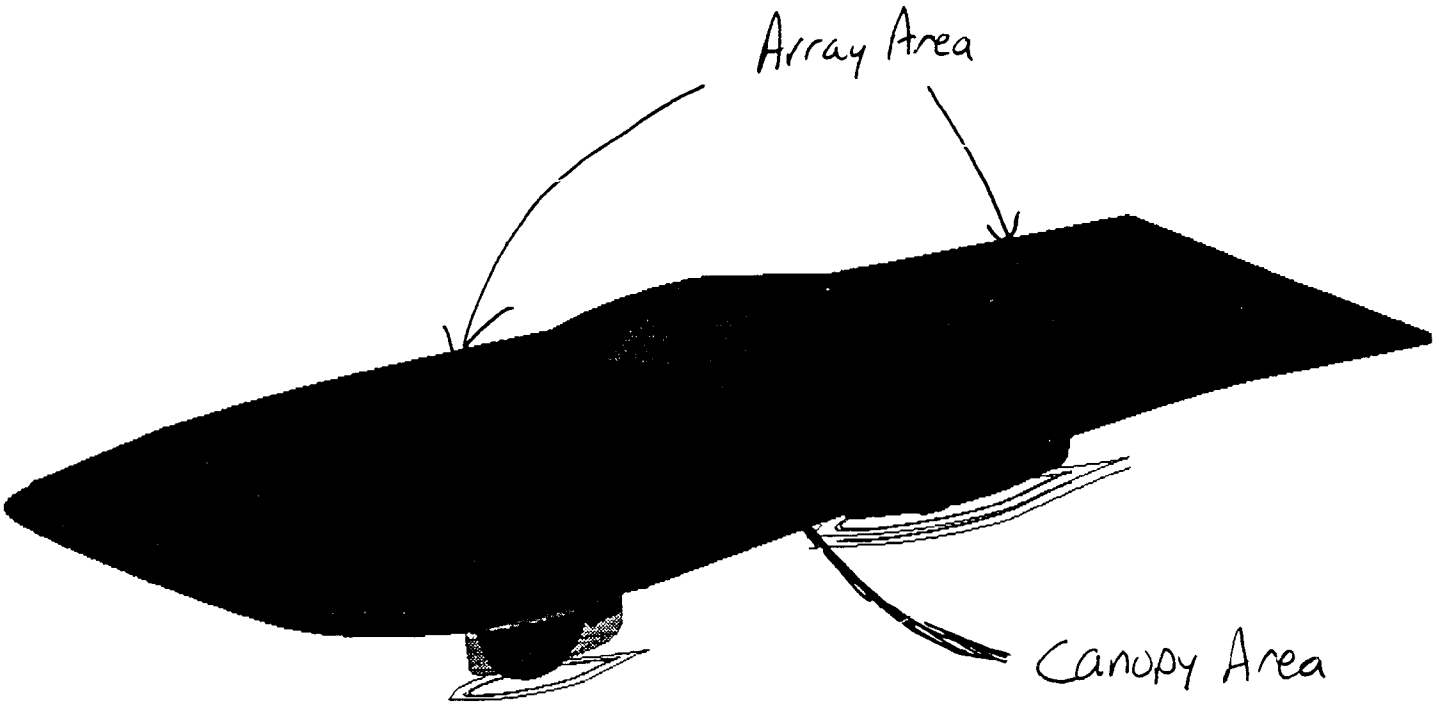


Figure 2. Isometric View of Shell and Array

Borealis' chassis is designed to transfer the static and dynamic loads from the driver and other components to the suspension mounts. In addition to the basic structural performance, the frame must protect the driver in the event of a front, rear, or side crash impact and in a roll over situation.

These performance requirements must be accomplished with a light weight frame. The predicted vehicle weight is 550 lbs including batteries and driver. The entire rolling mechanical chassis is targeted to weigh 135 lbs, with the composite frame accounting for 25 lbs. The chassis provides space to accommodate the driver, batteries, and all other subsystems, such that, the resulting center of gravity is located behind the front axle line by distance approximately equal to 1/3 the vehicle's wheelbase. This configuration was developed to produce desired handling characteristics and equalize tire wear. The resulting wheelbase is 90 inches, with a front track of 51 inches. By placing the batteries in front of the driver, rather than in the conventional behind-the-driver location, it is possible to achieve the desired center of gravity. Moreover, this layout significantly lowers the driver's exposure to inertial loads in the event of a front end collision and also surrounds the driver with large crush zones. (See Figure 3)

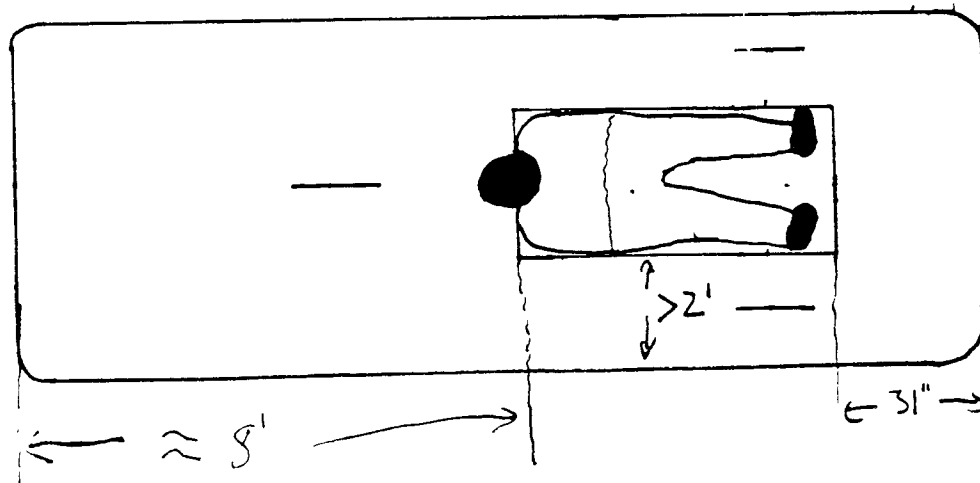


Figure 3. Crush Zones for Driver Protection

BODY DESCRIPTION

CONFIGURATION AND CONSTRUCTION

The body serves two primary functions: to act as an aerodynamic shell and to provide a platform for the solar array. It is not designed to support high localized loads and is designed to collapse in a crash situation. The body is a composite sandwich laminate consisting of two layers of carbon fiber mat on either side of a 0.25 inch Nomex honeycomb core bonded with a Epon 9500/Epi-cure 9550 resin system. It is fabricated in two parts (top and bottom) using a wet lay-up with a room temperature cure.

There are several main bulkheads in the body to provide support and mounting points. There are two bulkheads running the length of the body from the front to the rear in both the top and bottom halves. There are also three bulkheads spanning the width of the body on both the top and bottom halves. One just in front of the driver's feet, one just behind the drivers back, and another at the rear tail of the car. These bulkheads are made out of 0.400 inch thick prefabricated composite sandwich panels purchased from Hexcel Corporation. The panels consist of one layer of woven carbon fiber on either side of a Nomex core. They are positioned in such a way as to prevent the shell from translating relative to the chassis in a front or rear collision. The body may also contain secondary bulkheads used to stiffen the upper array surface. The areas in front of the front bulkhead and behind the rear bulkhead are not intended to be structural. Instead, this area is designed to collapse in a collision situation.

The body attaches to the chassis in four places, two each on the latitudinal bulkheads in front and behind the driver. The latching system used allows the top half of the body to be taken off of the car for road side maintenance. The latches use springs to push the body upwards enough for the body to be lifted off.

Driver egress is achieved by removing the canopy area from the shell. This permits the driver to stand up and get out of the vehicle in a quick and safe manner.

BODY INTRUSION PROTECTION

The standard solar car design composed of a wing shaped profile and bubble style canopy, as used in Borealis, can pose a severe risk of driver decapitation in the event of a collision if safety concerns are not properly addressed. In the Borealis design, this danger is addressed by a redundant set of safety features.

The goal is to negate the potential shearing action in the area around the drivers head caused by the relative motion of the body to the chassis. The area within which the driver resides must remain uncompromised in all potential crash conditions. To accomplish this goal, the aerodynamic shell of the car is designed to be much weaker than the chassis with regard to impact loads applied parallel to the ground plane. Therefore, the shell will collapse rather than translate relative to the chassis . Also, a system of lateral bulkheads in the body do not allow the body to translate as a unit relative to the chassis. One bulkhead immediately behind and one ahead of the chassis restrain its motion. As a secondary measure the roll cage is designed to "encourage" the body to slide up and over the driver's head in the event the lateral bulkheads fail to prevent body translation. From all directions, a translating body will impact inclined roll cage tubing. (The front anti-capitation bars are tilted back, the rear gussets are tilted forward, and the roll hoops are inclined from the side.) This will force the body upward, thereby protecting the driver's head.

CHASSIS DESCRIPTION

CONFIGURATION

The chassis is constructed from prefabricated composite panels purchased from Hexcel Corporation. The bottom panel is part of the aerodynamic shell. This part was fabricated by our team members. The structural chassis panel in the shell is the same material and thickness as the prefabricated composite panels. The prefabricated panels were assembled to the aerodynamic shell and follow its curved shape. Carbon Fiber panels were chosen for low weight, high stiffness, and high ultimate strength. The panels are assembled to form a monocoque structure resembling a box beam. The box beam geometry used in our chassis is relatively simple, with mostly 90-degree joints. The curve of the aerodynamic shell that the chassis follows creates the only on-90-degree joints. The 90-degree joints simplify construction and promote high quality joints. The composite panel chassis' were successfully tested with the last three solar cars built, the Aurora 2, Aurora³, and Aurora 4.

? ✓

For Borealis, the Mechanical team fabricated a mock-up plywood chassis. The mock-up was used to view what the driver cockpit would look like and to make the necessary changes. It was also used as an integration tool to see the possible component layouts. A complete vehicle assembly was created using Pro/Engineer CAD software to enhance the integration between all vehicle parts. The combination of these tools enabled the team to better judge drive placement, layout of components, and integrate vehicle systems.

The driver is surrounded by the frame which restrains the driver in the event of a collision. All panels surrounding the driver are considered structural. A high moment of inertia is achieved by tying the top and bottom planes by a vertical panel on each side of the driver compartment. Care was taken such that all loads are transferred into the chassis in a direction parallel to at least one prefabricated panel. The frame integrates places for driver displays, switches, and other various electrical components.

The roll cage is made of two parts. One is a system of tubing which resembles the traditional roll hoop. Also part of the roll cage are two anti-capitation bars placed in front of the driver. Anti-capitation bars are on each side of the driver consisting of a vertical tube and a rear angled tube. The vertical members deflect the aerodynamic shell away from the driver. Care is taken to distribute the roll cage loads into two or more shears planes at each attachment point thus spreading the forces to a wide area of the chassis. (this will be discussed further in the roll bar analysis section)

MATERIALS

Hexcel Composites' Fibrelam® 2000 prefabricated panels were used throughout the frame. These composite panels are typically used for aircraft flooring. These sandwich panels have a nominal thickness of 0.400 in. consisting of two 0.010 in woven carbon fiber sheets separated by 0.380 in Nomex core of 5-lb/ft³ density. Additional composite panel information can be found in the appendix. (Appendix A)

CONSTRUCTION

The composite panels came in 4 by 12 foot sheets. The frame parts were cut from the larger sheet using a CNC water-jet cutting machine at PAR Systems, Inc. This allowed for a close tolerance o parts and facilitated joint construction.

The joining technique chosen was tested successfully on the Aurora 2, Aurora³, and Aurora 4's frames. The panels are joined at 'T' and 'L' joints using a structural adhesive, 3M™ Scotch-Weld™ DP-460. The DP-460 was also used to create fillets at the corers of the 'T' joints.

The DP-460 epoxy system has a tensile shear strength of 4500-psi under the curing specifications used. The typical "T" joint used creates a shear area of approximately 0.4 square inches of shear area per joint inch. (See Figure 4). The joint can be assumed to carry a maximum shear load of $(0.4)*(4500) = 1800$ -lbs per joint inch.

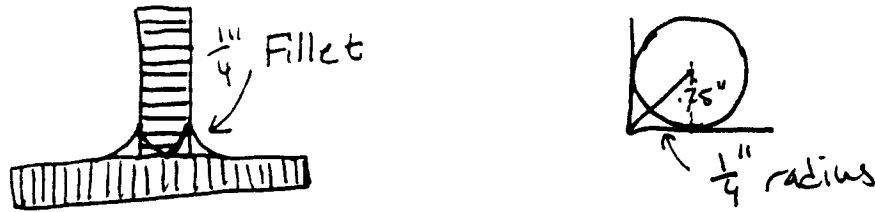


Figure 4 "T" Joint Detail

PREFABRICATED PANEL STRENGTH ANALYSIS

The data to four point bending tests were provided on a product data sheet to us by the manufacturer. These tests show an ultimate load of 285-lbs and a 0.46-in deflection at 100-lbs. The ultimate strength and elastic modulus of the carbon fiber skin layers were found using this information. These material properties are valid along the fiber direction at which tests were performed. Fortunately, all panels have their primary loading configuration along fiber directions. The ultimate tensile strength of the face sheets was found to be 62,500-psi. The Elastic Modulus was found to be 2.19×10^7 -psi. (See Appendix A for calculations)

It can be argued that the face sheets have a semi-isotropic behavior, meaning in plane material properties change little with respect to orientation. This argument is valid because the skin sheets are woven carbon fibers perpendicular to each other. Therefore, strength numbers found from four point bending tests can be extrapolated to all potential loading configurations provided appropriate safety factors are applied.

CHASSIS FEATURES

CENTER OF GRAVITY LOCATION

A vehicle's center of gravity (CG) is a crucial feature affecting stability, tire wear, and braking performance. Driver safety depends on these factors and therefore the CG location is considered with utmost importance. When a vehicle configuration was chose, special attention was paid to what was needed for the CG location. A three-wheel configuration was chose by the team. A 90-in wheel base was selected for the car based on the success of handling of the past solar cars the Aurora 2 and Aurora³. The track length was chosen by the estimated height of the center of gravity. This set the track length at 51-in. A three-wheel configuration meant that the target CG location would be on the longitudinal centerline, as low to the ground as possible, and 1/3 of the way toward the rear from the front axle line. Using a spreadsheet, the driver^{ad} components were adjusted to achieve the desired CG location. The configuration decided upon resulted in approximately 36% of the vehicle weight on the rear wheel and 32% of the vehicle weight on each front wheel. The approximate component placement and resulting CG location is given in the table below.

Table 1. Three Dimensional Center of Gravity Location

Estimated CG Location for Borealis in Racing Configuration			
Weight (lbs)	X Direction (in)	Y Direction (in)	Z Direction (in)
550	33	0	17.5

Note: The measurements are based on a right hand coordinate system with +X pointing rearward from the front axle and +Z pointing upward from the ground.

BRAKE SYSTEM

Borealis uses two entirely independent braking systems. The systems are identical and are each composed of two hydraulically operated disc brakes that act at the front wheels upon custom 8" D aluminum discs. Special lining is used for these discs. The pedal assembly actuates both brake systems and can be adjusted for balance.

A 51-inch track and a 90-inch wheelbase were used for Borealis. This configuration results in a vehicle with approximately equal static weight on all three wheels and approximately 25% weight transfer to the front under a theoretical 1.0 G braking situation.

STEERING SYSTEM

Borealis' steering system is very similar to that of Aurora³. The team decided to use a steering wheel for this car. This resulted in a lot of similar component sizes as Aurora³. All of these steering arm sizes were tested on the last few cars and worked with great success. The issues of Ackerman and bump steer were also considered in the design of the steering system.

SUSPENSION SYSTEM

Front Suspension

Material Specifications

The front suspension is a double A-arm design, with 60 degrees between arms to evenly distribute loads. The lower A-arm is made of 3/4" OD x 0.049 wall thickness Chrome-Moly Steel tubing. There will also be a steel attachment bracket welded onto the lower a-arm for the spring/shock unit. The upper A-arm is made of 5/8" thick 7075-T6 Aluminum. Both A-arms

have spherical bearings in housings built into the members. The inner ends of the a-arms are connected to the chassis by 3/8" and or 7/16" rod ends. The A-arm brackets incorporate chassis panels and 6061 Aluminum brackets. The chassis panels are angled so that they are in line with the A-arms and spring/shock unit, so as to receive loads in tension and compression only. The uprights are custom milled from 7075-T6 Aluminum. The hubs are also custom milled from 7075-T6 Aluminum. The brake rotor is made of 5/8" thick anodized Aluminum. The axle will be made of 17 mm diameter, heat-treated steel. We will be using NGM wheels and Bridgestone Ecopia tires.



NO

Loading Conditions

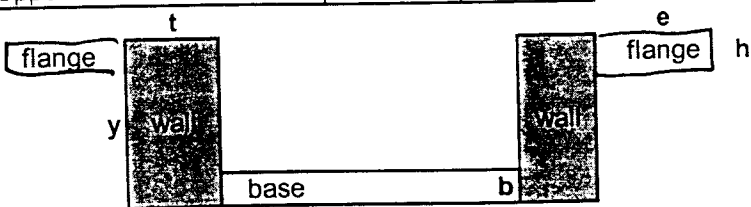
The front suspension components were analyzed under the loading conditions of static 1G, 4G bump, 1G cornering, and 1G braking. Free body diagrams and equations were developed and then put into a spreadsheet to analyze loading combinations to identify the worst loading cases. The force analysis can be found in the system analysis section.

System Analysis

DIAGRAM of sasp is needed

Upright Cross Section

Moments on Upright			
Location		M front view	M side view
Axle	0	2643	3088
Lower A-arm	4.15	4182	4908
Upper A-arm	9.75	0	0



- Flange width (e) = 0.5 inches
- Flange thickness (h) = 0.2
- Wall thickness (t) = 0.1
- Wall height (y) = 1.5
- Base length (x) = 3.0
- Base thickness (b) = 0.1

Table 2 Upright Cross Section

$$\bar{y} = \frac{\sum Y_i A_i}{\sum A_i} = \left(\frac{2(.2 \times .5 \times 1.5) + 2(.1 \times 1.5 \times .75) + (.1 \times 3 \times .05)}{(.2 \times .5) + (.1 \times 1.5) + (.1 \times 3)} \right) = 0.65 \text{ inches}$$

$$\bar{X} = 3.2 / 2 = 1.6 \text{ inches}$$

$$\bar{I}_x = 2(.65^2 \times .2 \times .5) + 2(1/3 \times .1 \times .85^3) + 2(1/3 \times .1 \times .65^3) + (.55^2 \times .1 \times 3) = .234 \text{ in}^4$$

$$\bar{I}_y = 2(1.6^2 \times .2 \times .5) + 2(1.5^2 \times 1.5 \times .1) + .1 \times 1.5^3 / 12 = 1.215 \text{ in}^4$$

$$\sigma_{\text{front view}} = Mc / I_c = 4182 \times (1.5 - .65) / .234 = 15162 \text{ psi}$$

$$\sigma_{\text{side view}} = Mc / I_c = 4908 \times 2.1 / 1.215 = 8483 \text{ psi}$$

For Aluminum $S_{\text{yield}} = 70000 \text{ psi}$, therefore the Safety Factor = $70000 / 15162 = 4.6$

Force Analysis in A-arm members

bump, braking, corner g's	4 0 0	4 1 0	4 0 1	4 1 1	0 1 0	0 0 1	0 1 1
R1	179	971	-431	361	792	-610	182
R2	179	-613	-431	-1223	-792	-610	-1402
R3	-1327	907	-1327	907	907	-1327	907
R4	650	-467	-210	-1327	-1117	-860	-1977
Fsp	1270	1270	1270	1270	0	0	0

Table 3 Force Analysis in A-arms

All forces are in lbf. R1 = Upper front link, R2 = Upper rear link, R3 = Lower front link, R4 = Lower rear link.

A-arms as columns

Modeled as a fixed-pinned column

Effective length $L_e = .8 * L$

Lower A-arms (steel tubing)

$$P_{\text{critical}} = \pi^2 EI / L_e^2 = \pi^2 (30,000,000)(.006) / (12.44)^2 = 11500 \text{ lbf}$$

$$\text{Safety Factor} = P_{\text{critical}} / P_{\text{actual}} = 11500 / 1977 = 5.8$$

Upper A-arms (5/8" square Aluminum)

$$P_{\text{critical}} = \pi^2 EI / L_e^2 = \pi^2 (10,000,000)(.625 \times .625^3 / 12) / (8.6)^2 = 16968 \text{ lbf}$$

Diagram needed

$$\text{Safety Factor} = P_{\text{critical}} / P_{\text{actual}} = 16968 / 1402 = 12$$

Conclusions

The results of the analysis of the front suspension led us to believe we could improve on our previous Aurora cars suspension designs. With a lighter car, we were able to package components in a better fashion, and save weight as a result. We can also come to the conclusion, based on the safety factor calculations, that we will have a safe front suspension.

Rear Suspension

The rear suspension of Borealis is a trailing double a-arm with a vertically mounted shock and spring assembly. The a-arms are constructed from 5/8" thick 7075-T651 aluminum and water-jet cut to tight tolerances. The inner ends of the lower a-arm are attached to the chassis with 3/8" rod ends that are loaded only in tension and compression. The inner ends of the upper a-arm are mounted to the chassis with 5/8" spherical bearings enclosed in custom-built housings because of the additional force applied by the toe-in support member. The inner ends of the a-arms mount to the chassis with custom aluminum brackets designed to transmit the suspension loads into ~~at least~~ two different chassis planes. Spherical bearings are also used to mount the a-arms to the suspension upright because of the multi-directional forces applied at these points. The suspension upright is milled from 7075-T651 aluminum and is custom designed for mounting the a-arms, toe-in support member, in-wheel motor and spring/shock assembly. The spring/shock assembly is a coil over design manufactured by ~~Fox~~ ^{CORVER} Racing. The spring/shock mounts vertically, directly above the wheel-axle between the suspension upright and a crossbeam mounted between the fore/aft chassis members. Mounting the spring/shock vertically has the positive effects of reducing the forces transmitted through the a-arms and mounting brackets and improved

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damping of the large unsprung mass of the in-wheel motor. The crossbeam is constructed from 6065-T6 aluminum and is designed to accommodate a bending load of over 1000 lbs.

Load causes
Bending moment

COMPOSITE MOUNTING

Two part composite inserts were used at all locations that required bolting to the composite panels. They are tested by the manufacturer to 1,500 lbs in-plane shear. The design of the insert is intended to handle bolting clamp load while distributing axial and shear loads to the sandwich panels. These fasteners were used successfully on both Aurora I, Aurora II, Aurora³ and Aurora 4.

All suspension brackets have been designed to be light weight and serve multiple purposes.

Suspension mounting brackets incorporate three features:

- a) Each bracket attaches to at least two panels, thereby reinforcing the bonded joint between the panels.
- b) Loads applied to the brackets are spread to at least two panels.
- c) At least one of the panels that attach to a bracket is loaded in-plane, so a worst case "shear only" analysis can be performed using the grommet specification.

BATTERIES

Battery Layout

The battery box is made of a non-conductive material and is positioned in front of the driver.

Nope

This arrangement has many safety benefits. In a frontal collision or roll over situation, no inertial battery loads are directed at the driver. At least one panel must fail to allow the battery force or

battery acid to contact the driver. The composite panel performance in a crash scenario is addressed in the various crash analysis sections.

In addition to the battery compartment, the box structure of the frame provides mounting positions for the electrical components. The electrical components are self-contained in insulated boxes. The sealed boxes reduce the risk of short circuits due to environmental contaminants.

Battery Mounting

The battery box is a removable battery box. It is mounted to the longitudinally running bulkheads in front of the driver. The box will be inserted from the side of the vehicle and is primarily designed for our Lithium-Polymer battery pack

NO

DRIVER RESTRAINT

Drivers Compartment

The drivers safety capsule is designed to remain unviolated in the event of a collision and constrain the driver inside. The 20.0 inch driver's compartment width holds most drivers snug from left to right which would be beneficial in a side impact. Also, the drivers lower extremities are constrained within the drivers compartment from all sides and cannot "flail" in an accident. The side panels are 10.525" high at the driver's shoulders, and when belted in, only the driver's head is above the upper plane of the chassis. The driver head is constrained from moving rearward during a rear impact by a padded headrest. This reduces the risk of a whiplash injury.

Safety Harness

A six point safety harness will be utilized in Borealis. The harness attachment points are located at the intersection of two or more panels, providing strength in multiple directions. The driver is reclined at approximately 27 degrees from horizontal. This configuration is similar to that addressed in SAE's Baja Buggy Competition Rules. These rules provided a guideline for harness mounting point location. The shoulder belts are secured below the top of the shoulder, constraining the driver in the event of a roll over. (See Figure 5) The lap belts are positioned three inches ahead of the intersection of the belly pan and the seat back. This ensures that the belts cross the hips and not the lower abdominal region. The submarine belts secure to the same location holding the driver in a frontal collision. The mounting brackets are bolted through the composite using composite inserts to distribute loads and transfer them to the panels.

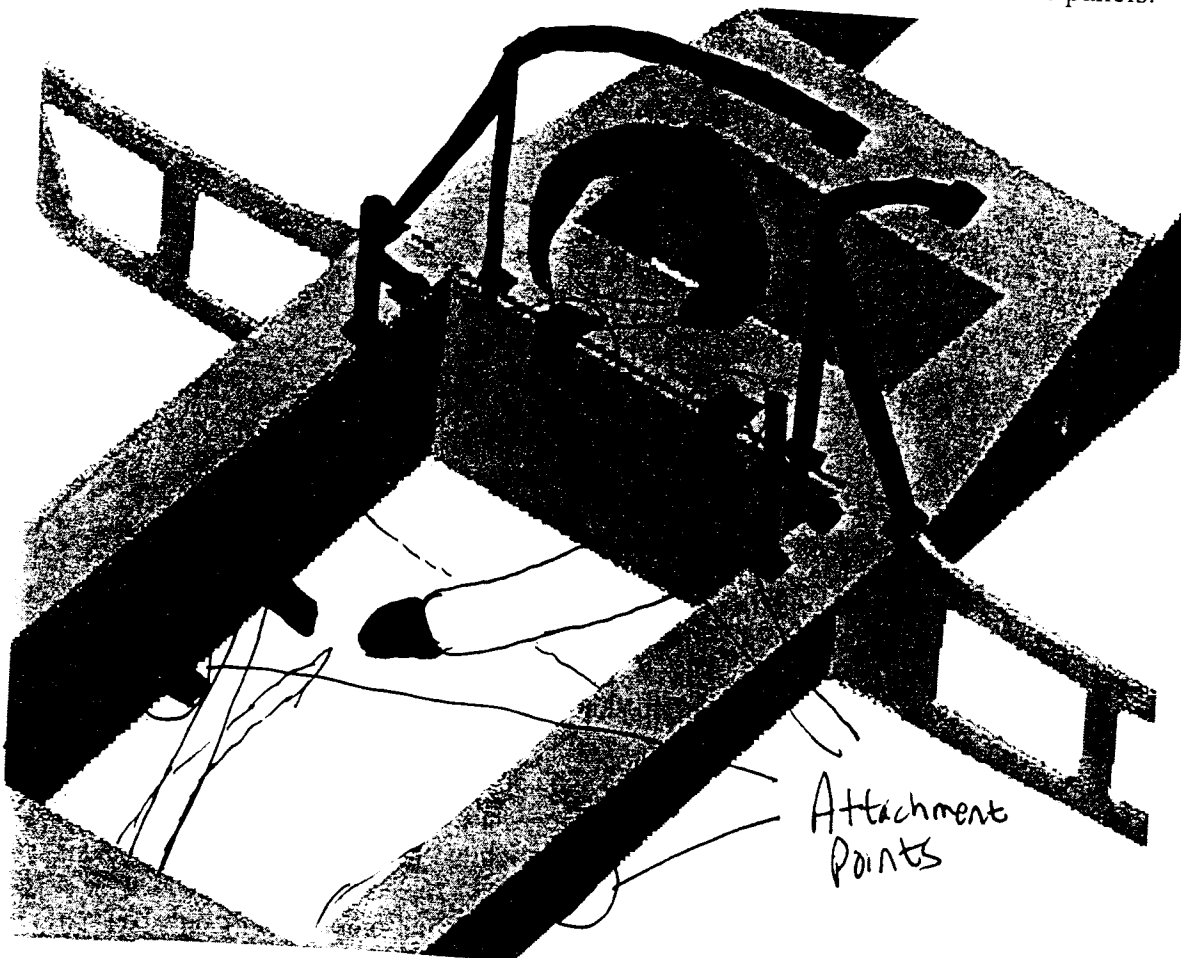


Figure 5. Safety Harness Attachment Points

Figure 5 Safety Harness Attachment Points

VEHICLE CRUSH SPACE

In the event of a collision, a system of progressive safety features will prevent the driver from being injured. The Borealis design places the driver within a safety capsule, with no part of his or her body extending beyond the structural chassis. The driver's shoulders are positioned below the upper plane of the chassis, such that, the torso, containing most vital organs, is located in the center of the structural chassis. The driver's head will be encompassed by a roll cage structure designed to protect the vulnerable driver's head which protrudes through the car's body.

ASC rules require 5.9 inches (15 cm) horizontal distance between the driver's shoulders, hips and feet and the car's outer body surface. (Section 5.3.5) Borealis' minimum crush space of greater than 2 feet is over **four times that required by ASC rules**. This large crush space around the driver was made possible by locating the cockpit in a central location in the car. (See Figure 4)

In a rear collision, the 8 feet of solar car behind the driver will act to absorb much of the impact energy. Likewise, in side collisions the driver resides in the center 20 inches of the 5.9 foot wide car, allowing over 2 feet of crush zone on either side. The shell material will crush and then driver is then protected by the driver's compartment as show in the various crash analysis sections.

Front crush space was maximized beyond race rule requirements with 31 inches of crush space. The 31 inch nose of the car will crush easily, while allowing the crash to be stopped by the structural chassis. The front batteries will help block penetrating objects and decelerate the impacting body due to their mass.

CRASH LOADING ANALYSIS

FRONT AND REAR END 5G COLLISIONS WITH THE SPECIFIED

BUMPER

The loading on various panels will be traced, and specific joints and panels will be analyzed for strength using accepted procedures based upon the properties of the panels and the bonding agent properties.

Front End Impact at 5 G

The bumper height ranges from 13.8 inches (35 cm) to 17.7 inches (45 cm) and the front chassis lateral bulkhead ranges from 11 inches to 23 inches. Thus the bumper will squarely hit the chassis bulkhead, once the nose of the body collapses. The body will not move rearward, since the front lateral body bulkhead is approximately one half inch ahead of the front chassis bulkhead. The impact will merely demolish the fragile nose of the body, then the body bulkhead

will simply be pushed rearward, about 1/2 inch, into the chassis bulkhead. Thus, the bumper force will now be upon the front face of the chassis.

Figure 8 shows a top view of the chassis at this stage, with the inertia forces of the major components:

- The front batteries (66 lb)
 - The driver (176 lb)
 - The body (110 lb)
 - The chassis, electrical components and suspension (198 lb)
- (Total weight is 550 lb)

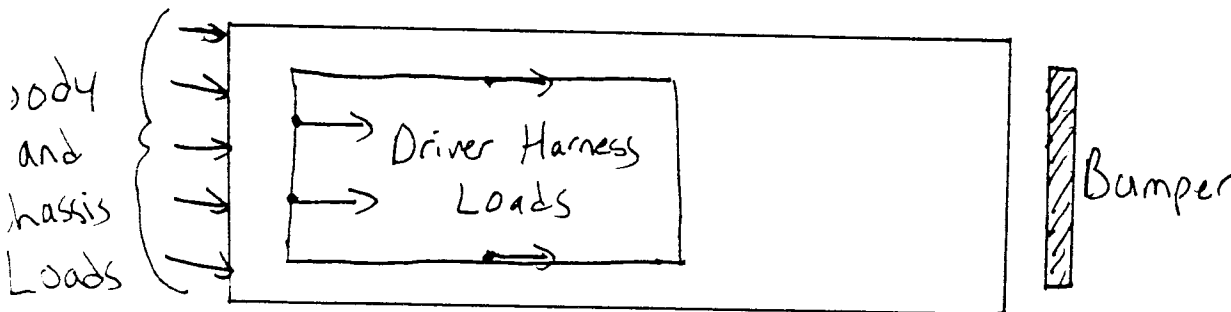


Figure 6. Assumed Loads in Chassis

Each of these component weights is multiplied by five to estimate the 5 G loading. The center of mass of the front battery pack is within the bumper height, and the battery pack is in front of the front bulkhead, so the inertia force due to the front battery pack acts directly upon the bumper. It does not load the chassis in a front end collision. Thus the load on the chassis can be reduced by the 5 G force on the front battery pack or:

$$\text{Force from bumper upon chassis} = 5 \cdot (550 - 66) = 5 \cdot (484) = 2420 \text{ lbs}$$

or we will use 2,500 lbs

This load will be initially felt by the two vertical panels, one on each side of the driver. The front chassis bulkhead is glued to these panels, and so will distribute the bumper load across the front vertical face of each panel as shown in Figure 7.

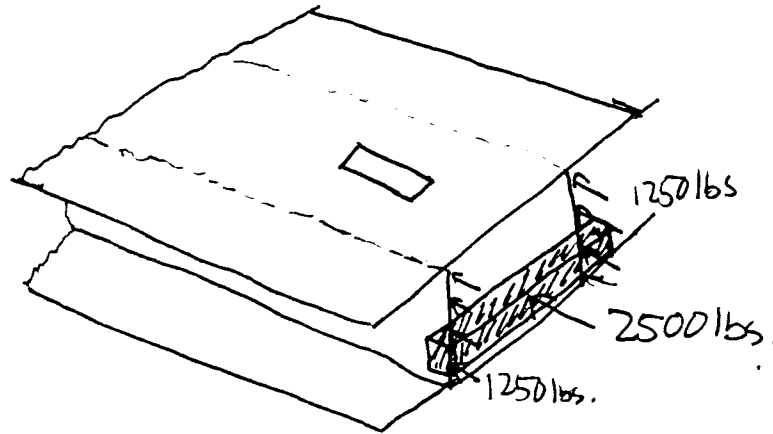


Figure 7. Net Bumper Loads on Vertical Panels

The following will argue that the forces are taken by these vertical panels and have sufficient strength to withstand the front bumper loads under very conservative assumptions. The upper and lower panels are used to provide edge stability to the vertical panels and are not figured into the crash analysis. The joint between the vertical panels and the upper and lower panels is shown to be strong enough to hold the crash force before the driver's feet can be reached and thus the

assumed. The inertia forces on the driver, body and chassis will all be assumed to be located at the rear of the driver's compartment, and will only be resisted longitudinally by the two vertical panels. These panels are a minimum of 10 inches in height and 66 inches long. This is a conservative estimate because it has been shown that the joint between the vertical panels and the upper and lower panels will not break. This would mean that some of the impact force would be transmitted to the upper and lower panels as well as the vertical panels.

Each panel of figure 9 has similar loading, so only one will be examined. The presumed mode of failure is buckling, and the critical stress level can be found using the methods in Successful Composite Techniques, by K. Noakes, Osprey Publishing, 1992, p 133-141. When

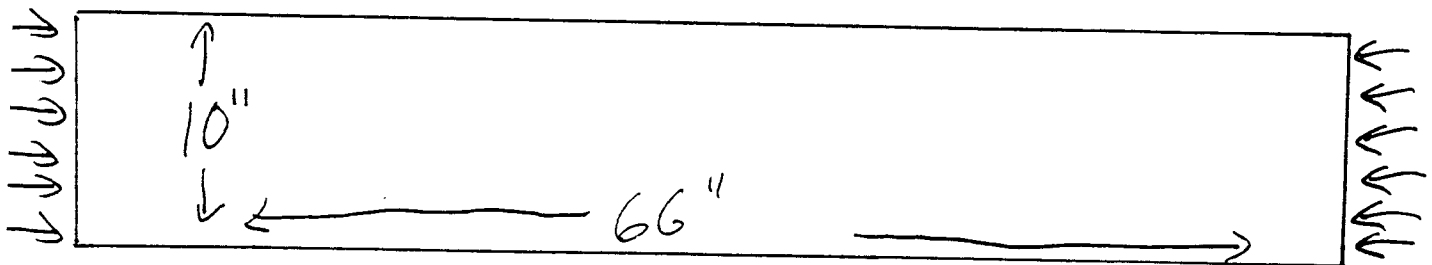


Figure 9 Assumed load on vertical panels

conservatively treated with simply supported edges, the buckling stress in the face sheets was calculated to be 199,859 psi. This figure greatly exceeds the maximum skin stress of 62,500 psi as determined from the panel specifications. The procedures in Noakes were checked many

times, so in the following, we will use the lower 62,500 psi stress level rather than the 199,859 psi value.

The actual compressive stress in the skin is simply the 1250 lb load divided by the skin area which gives a compressive stress of 6,250 psi. This is far below the 62,500 psi maximum value, giving a safety factor of 10. Thus the driver's compartment can easily withstand the 5 G front end impact.

Rear Impact With Bumper at 5 G

The trailing edge of the vehicle at nominal ride height is 19 inches, while the bumper ranges from 13.8 inches (35 cm) to 17.7 inches (45 cm). Upon impact, the bumper will go under the tail of the solar car, but the trailing edge will run into whatever part of the colliding vehicle is above its bumper. The tail section of the body will start to collapse and be driven forward. The roll bar has two rearward sloping supports and these will serve to tear apart the rear body shell before it could impact the driver's headrest, or to drive the body up and over the driver's head. Then the bumper will hit the rear wheel, which has a radius of 9.5 inches, while the rear of the chassis is about 12.6 inches above the ground. The bumper will hit the rear wheel above its axle line, thereby pushing it forward and downward. The spring-shock unit will reach its full extension and sever, while the suspension, wheel and motor will be forced below the vehicle chassis as the suspension rod ends fail, being rotated beyond their design limits without the constraint of the shock unit. Finally the bumper will contact the rear chassis bulkhead the same way as for the front impact. The bulkhead will distribute the load to the two longitudinal vertical panels. It has already been shown that these vertical panels can easily handle this 5G impact. The only difference here is the added front battery pack inertial loading. This creates an inertial loading of 2,750 lbs and a safety factor of over 9. The front battery pack is positioned in front of the front

bulkhead and is 36 inches wide. This is wider than the two vertical panels are apart which means these panels will stop the battery pack. Thus we can conclude the chassis will withstand both front and rear 5 G impacts with the specified bumper.

SIDE IMPACT at 5 G

The composite chassis was designed to isolate the driver in the event of a side collision. This was accomplished by constraining the driver within the center 20 inches of the 28 inch wide frame. Two transverse frame panels run the 28 inch lateral width of the car. Separated by 66 inches, one panel is in line with the roll over bulkhead, and one is just ahead of the drivers feet. The center of gravity of the vehicle is located approximately midway between these panels.

The 5 G side impact force was considered to act as a plane perpendicular to the line of action of the force. This loads the chassis uniformly from the side. However, to be conservative, the plane will be assumed to react only against the two vertical panels which span the width of the frame. These forces can be thought of as simple supports, with the inertial forces reacting against them.

This crash loading reacts against all of the inertial loads in the car. These inertial loads act as locally distributed loads over the full length of the chassis. Since the CG of the vehicle falls between the supports, the load can be modeled as a simply supported distributed load of 550 lbs. Since the span of the distributed load is actually much wider than the width of the supports, the actual resulting bending moment would be lower, so this choice of loading is, again, conservative.

The chassis was designed to be a box beam. Therefore, simple beam bending analyses can be used with accurate results. The moment of inertia of the frame at its weakest point (at the drivers back) was calculated. This was done considering only the contribution of the fiberglass face

sheets. The Nomex core serves only to maintain the location of the face sheets. Due to the monocoque geometry, the resulting moment of inertia was considerably high. (See Appendix A) Utilizing simple bending theory, the frame was found to be capable of a safety factor of 5 on the 5G inertial loading. This load is plausible due to the high moment of inertia of the monocoque cross section. This value is far above the 5 G limit required by ASC rules, and is therefore safe.

Roll Over Scenario

Roll Cage Analysis

The roll cage consists of two separate triangulated structures on each side of the driver's head as shown in Figure 12. Two choices of materials are being considered: 1.25 in. O.D. x 0.049 4130 steel tubing and 1.5 in. O.D. x 0.065 6061 T6 aluminum. Each of these have the same EI product as the tubing specified in the rules, but weigh less. The steel structures will be welded and torch annealed to maintain strength, but not heat treated to increase the strength. The aluminum structure will be heat treated back to the T6 condition.

In a rollover condition, the driver's helmet is below the line from the forward edges of the roll bars and the front of the structural chassis, shown as AA in Figure 12, and below the line towards the rear of the structural chassis, shown as BB. In the front view the helmet is below the horizontal line between the verticals as shown in Figure 10 as line CC.

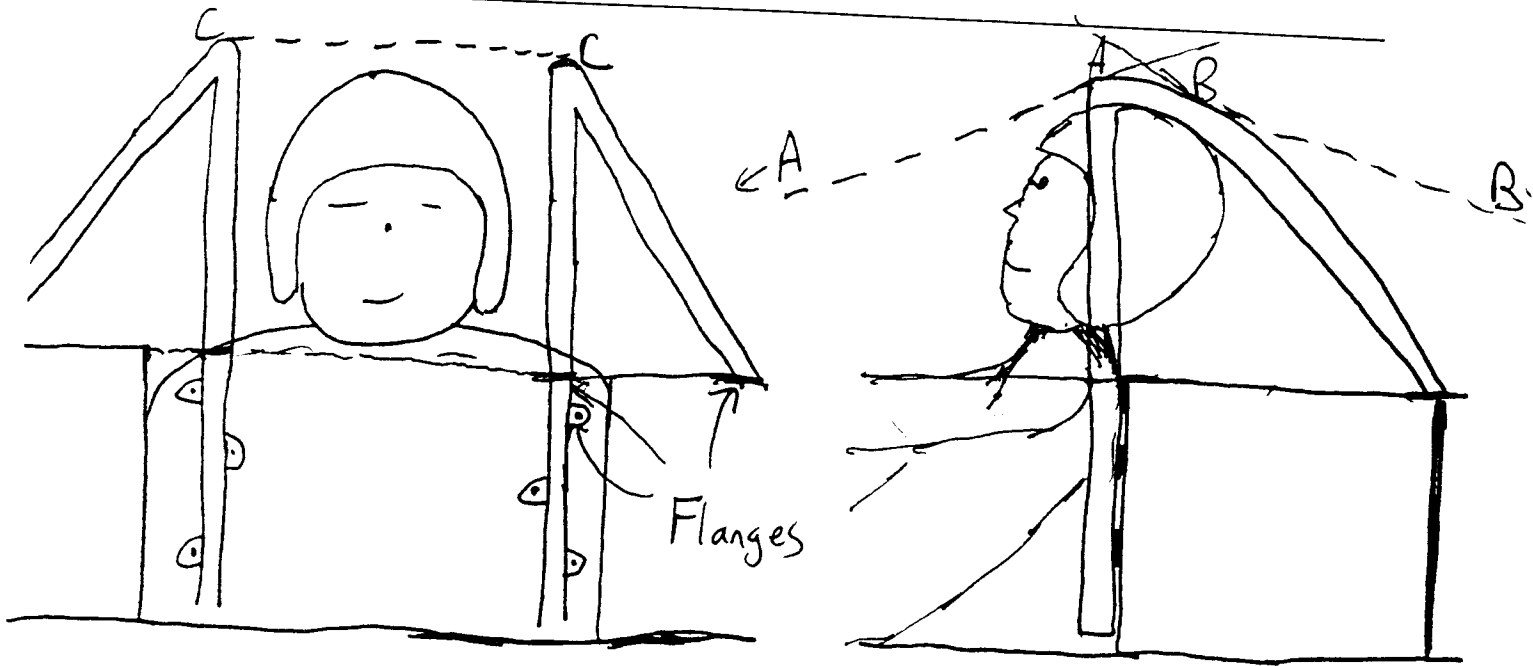


Figure 10 Roll Cage Configuration

In front of the driver's head are two anti-capitation bars. They are designed to deflect the aerodynamic body away from the driver's head in the event of a collision. They consist of two members: one vertical member which will actually deflect the body and one angle member which is used to support the vertical member. The anti-capitation bars are mounted onto the upper panel of the chassis.

The strength of the structures under various load condition's were estimated using analysis methods found in Roark's Formula's for Stress and Strain. W. Young, sixth ed., McGraw-Hill. Load cases are shown in Figure 11 and the details of the analysis are in Appendix C.

Loads in the vertical fore-aft plane W1, W2, W3 and W4 are applied to each structure together. That is W1 is one half of 3G times the vehicle weight. Lateral load W5 is applied to a single structure and is the full 3G load.

Appendix C shows that the maximum stress in each load case is below the material yield stress, and also finds the loads at the attachment points for selecting the number of grommets to be used.

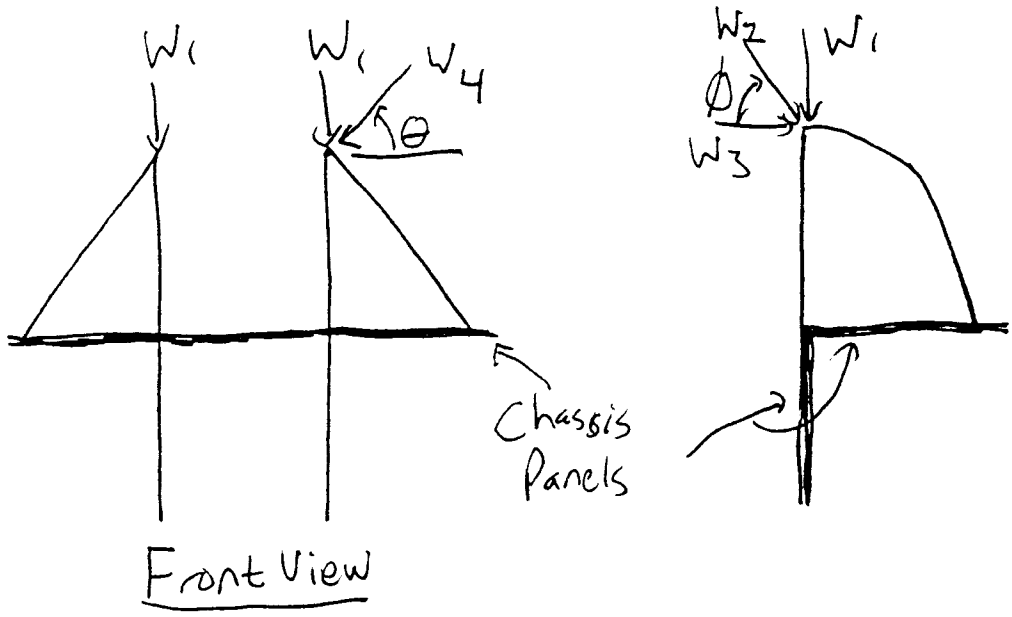


Figure 11 Roll Cage Loading

Typical Roll Over Situation

The typical roll over situation would see the vehicle transferring inertial load to the ground at two points: the roll bar peak and the front, upper corner of the frame. Notice, that in this configuration, the ground plane never violates the driver's compartment.

The chassis can then be modeled as a simply supported beam with the worst case scenario of the 3G inertial load acting at a point in the middle of the chassis. Again, the reacting force is a plane (the ground) acting against the inertial loads of the contents of the vehicle. As the analysis above demonstrates, the roll bar structure is rigid, completely transferring any load it sees to the frame, and beam analysis can be utilized.(see Appendix A)

The large moment of the monocoque cross section gives the structure a safety factor of 3 with the 3G inertial loading. Again, this is far and above the 3G's required by ASC rules.

Crash Load Increments Between Horizontal and Vertical

As Viewed from Front

These loading configurations can be inferred to be satisfactory from the calculations performed in previous sections. A planar load applied to the chassis from any angle between the vertical and horizontal, as viewed from the front, can never violate the drivers compartment. The plane will be forced to load up onto the roll bar hoop and the top plane of the chassis at its widest point. The resulting localized loads would be much lower than those shown above. Therefore, since the chassis has very large safety factors in the vertical and horizontal load directions these lower loads could only produce higher safety factors resulting in a safe condition.

As Viewed from Side

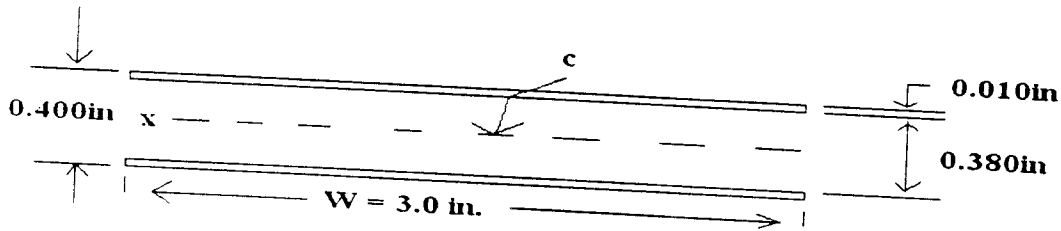
Again, any planar load between the vertical and horizontal loads would not violate the driver's cockpit. Instead, they would load up on the top of the roll hoop and the foremost portion of the top plane. The resulting localized loads would be much lower than those already found to be safe in preceding sections. Therefore, the chassis is deemed safe in all incremental loading situations as viewed from the side.

2) Using Sectional Analysis:

$$\Sigma M = M_{MAX} + P/2(A) - P/2(2A) = 0$$

$$M_{MAX} = P/2(A) = (285\text{lbs}/2)(5\text{in})$$

$$M_{MAX} = 712.5 \text{ in lbs.}$$



GIVEN: 1) $W = 3.0 \text{ in.}$ 2) Face Skin Thickness = 0.010 in

3) Total Thickness = 0.400 in

B) Find I_{xx}

1) Ignore Modulus of Core Material Since \ll Face Skin Modulus

$$2) I_{xx} = I_{0.400} + I_{0.380} \quad (I = (Wh^3)/12)$$

$$= ((3\text{in}(0.400\text{in})^3)/12) - ((3\text{in}(0.380\text{in})^3)/12)$$

$$I_{xx} = 0.00228 \text{ in}^4$$

C) Find S_{MAX}

1) Using the Flexure Formula

$$S_{MAX} = (M_{MAX} * c) / I_{xx} \quad c = 0.400\text{in}/2 = 0.200 \text{ in.}$$

$$= ((712.5 \text{ in lbs})(0.200\text{in.})/0.00228\text{in}^4)$$

$$S_{MAX} = 62,500 \text{ psi}$$

CALCULATION OF MODULUS OF ELASTICITY OF COMPOSITE PANEL

FROM QUARTER POINT BENDING TEST DATA:

GIVEN: 1) $\delta_{MAX} = 0.46 \text{ in. @ } P = 100 \text{ lbf}$ 2) $L = 4A = 20 \text{ in.}$

FIND: E

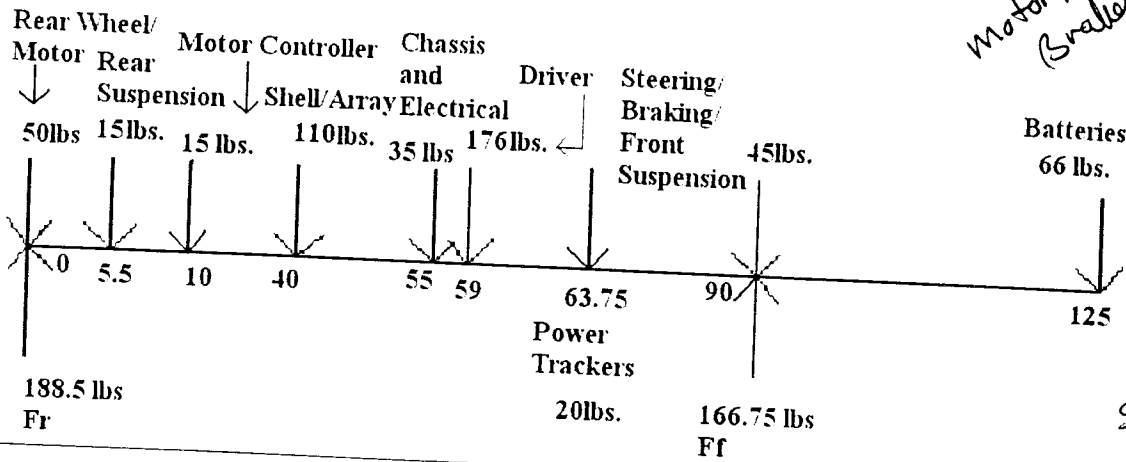
$$1) \delta_{MAX} = (PA/24EI) * (3L^2 - 4A^2)$$

$$= (44PA^3)/24EI$$

$$E = (11/6)(PA^3 / (I\delta_{MAX})) = (11/6)((100)(5 \text{ in.})^3 / (0.00228 \text{ in}^4)(0.46 \text{ in}))$$

$$E = 2.19 * 10^7 \text{ psi}$$

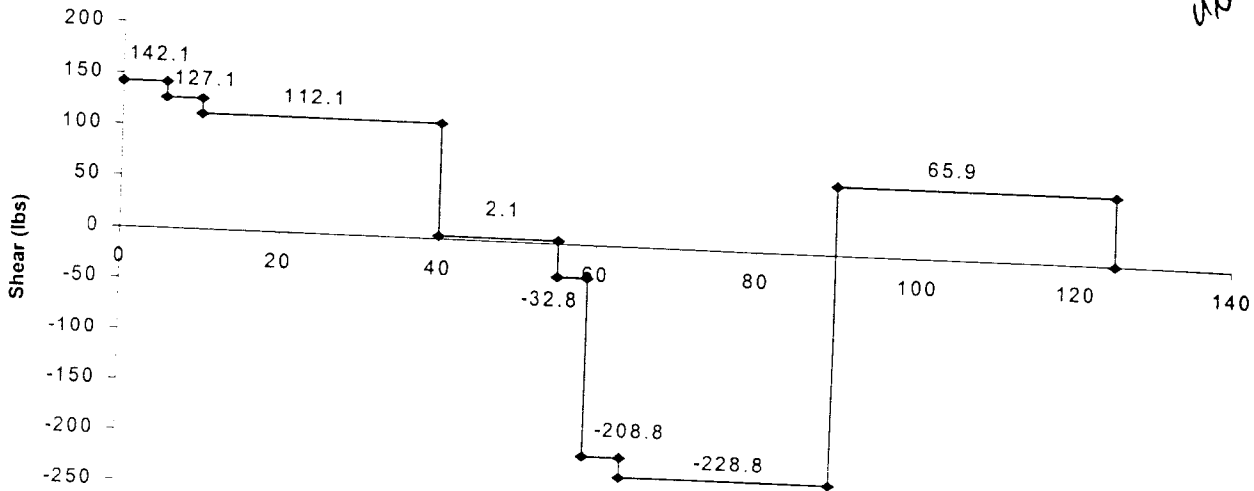
MOMENTS AND FORCES ON THE CHASSIS



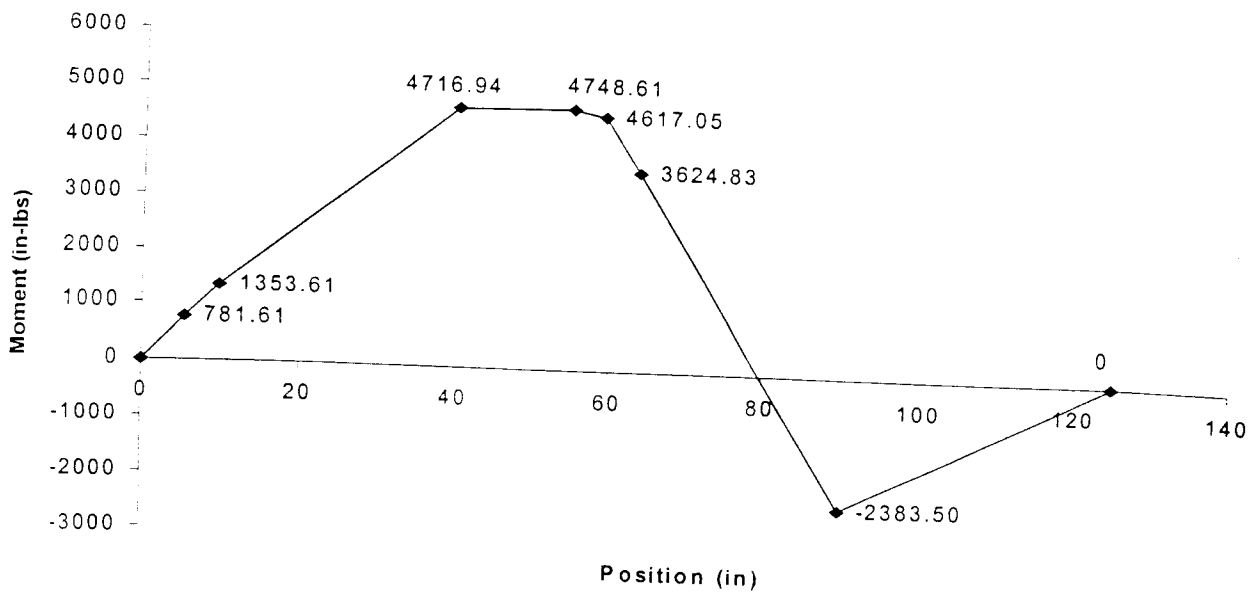
*Motor, wheels
 Brakes, upright
 weight
 on are
 ground
 not
 chassis*

*Need to
 separate
 spring f
 UNSURE
 WTS -*

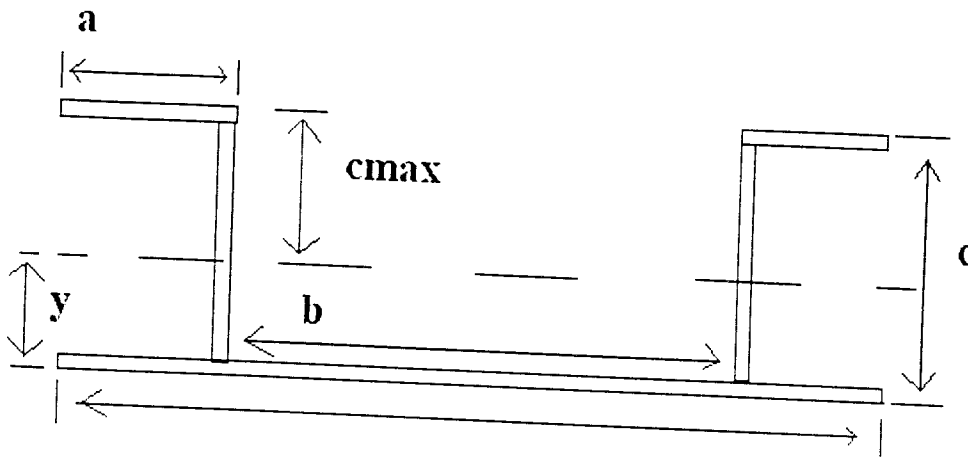
Shear Diagram



Moment Diagram



MOMENT OF INERTIA OF CHASSIS FRAME ABOUT HORIZONTAL AXIS



$a=4$ in. $b=20$ in. $c=11.083$ in. $d=\text{panel thickness}=0.400$ in. $e=\text{skin thickness}=0.010$ in.

1) Find y : $y = \frac{\sum y_i A_i}{\sum A_i} = \frac{2((c-(d/2))da) + 2((c/2)d(c-2d)) + ((d/2)(2a+b)d)}{(2da + 2d(c-2d) + (2a+b)d)}$

$y = 3.653$ in

2) $c_{max} = 11.083$ in $- 3.653$ in.

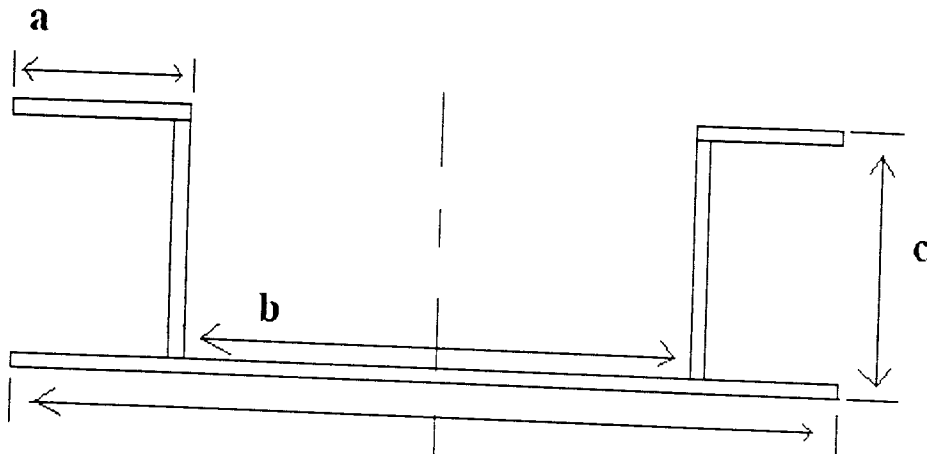
$c_{max} = 7.43$ in.

3) $I_{xx} = \sum (I_{NN} + AR^2)$

$$\begin{aligned} &(((2ae^3)/12) + (2aec_{max}^2)) + (((2ae^3)/12) + 2ae(c_{max}-d)^2) \\ &+ (((2a+b)e^3)/12) + ((2a+b)ey^2)) + (((2a+b)e^3)/12) + ((2a+b)e(y-d)^2)) \\ &+ (((4e(c-2d)^3)/12) + 4e(c-2d)(c/2-y)^2) \end{aligned}$$

$I_{BB} = 20.16$ in⁴

ABOUT VERTICAL AXIS



Find I_{yy} :

$$\begin{aligned} 1) \quad I_{yy} &= \Sigma(I_{NN} + AR^2) \\ &= 2\left(\frac{e(2a+b)^3}{12}\right) + 2\left(\frac{e^3(c-2d)}{12}\right) + (c-2d)e\left(\frac{b}{2}\right)^2 \\ &\quad + 2\left(\frac{e^3(c-2d)}{12}\right) + (c-2d)e\left(\frac{b+d}{2}\right)^2 + 4\left(\frac{ea^3}{12} + ea\left(\frac{b+a}{2}\right)^2\right) \\ &= 101.467 \text{ in}^4 \end{aligned}$$

STRENGTH OF CHASSIS

$$\sigma = Mc/I$$

$$M_{\max} = 4748.61 \text{ in-lb g's}$$

$$c = 7.43 \text{ in}$$

$$I = 20.16 \text{ in}^4$$

$$\sigma_{\max} = (4748.61 \text{ in-lb} * 7.43 \text{ in}) / 20.16 \text{ in}^4 = 1750.11 \text{ psi g's}$$

$$\text{S.F. in g's} = 62500 \text{ psi} / 1750.11 \text{ psi} = 35.71 \text{ g's}$$

Appendix B: Borealis CG Inventory

Borealis CG Estimate					
Item _i	Description	W _i (lb)	L _i (in)	L _i x W _i	
1	Rear wheel, Motor...	40	90	3600	
2	Motor Controller	20	80	1600	
3	Rear Susp, arms, shock, spring, bracket	15	84.5	1267.5	
4	Shell, Array, Fairings	110	49	5390	
5	Driver & Ballast	176	30	5280	
6	Chassis, Roll Bar	25	35	875	
7	Steering, Braking, Pedals	20	0	0	
8	Front Suspension, arms, springs, shocks, brackets	40	0	0	
9	Power Trackers	20	16.25	325	
10	Electrical	15	35	525	
11	Batteries	66	-15	-990	C.G.
		547	404.75	17872.5	32.6736
					7