

# Design, Manufacturing, and Verification of a Steel Tube Spaceframe Chassis for Formula SAE

by

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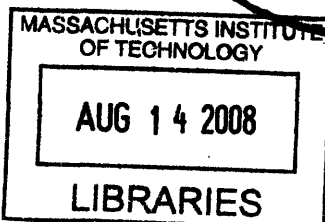
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**Alexander M. Soo**

**Submitted to the Department of Mechanical Engineering  
on May 8<sup>th</sup>, 2008 in Partial Fulfillment of the  
Requirements for the Degree of Bachelors of Science in  
Mechanical Engineering**

## **Abstract**

The Formula SAE chassis provides a number of functions: it protects the driver during high speed operation, links critical components such as the engine, drivetrain, and suspension together through a rigid structure, and distributes forces through the frame to allow for predictable handling and kinematics. This document examines and analyzes the critical factors in designing and building a Formula SAE chassis from 4130 chromoly steel tubing. The paper focuses on several main design issues and criteria, provides a detailed description of the manufacturing and jiggging process, and also documents verification testing of the real chassis against the CAD and FEA models. The thesis will serve three functions: first as a summary of lessons I have learned about product development from personally overseeing the fabrication of the MIT Motorsports chassis for 3 years (MY2006 - MY2008), second as a guide for future generations of chassis engineers in frame design and construction, and third as a specific study and verification of the theoretical methods behind the current vehicle design.

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## 1.0 Introduction to Formula SAE

Formula SAE is a series of engineering competitions run by the Society of Automotive Engineers (SAE) to design, build, and race small F1 style, open wheel vehicles among universities around the US and worldwide. The overall goal of the competition is to provide a prototype for a weekend autocross vehicle, sold to a hypothetical racing enthusiast for less than \$25,000. In order to succeed, teams must focus designs on excellent engineering, cost, reliability, and performance.

The competition is divided into static and dynamic events to evaluate both the design of the vehicle and its performance under a number of conditions. Figure 1 summarizes the different point breakdowns of each aspect of the competition. It is important to clearly understand the competition details in order to fully comprehend the level of engineering quality and detail that must be incorporated into these Formula SAE vehicles. They are evaluated and raced to the highest standards, in extremely rigorous conditions. In order to succeed, these vehicles and their components must be able to perform at a high level, and also withstand racing conditions for an extended period of time.

<b>Static Events</b>	
<b>Presentation</b>	75
<b>Engineering Design</b>	150
<b>Cost Analysis</b>	100
<b>Dynamic Events</b>	
<b>Acceleration</b>	75
<b>Skid-Pad</b>	50
<b>Autocross</b>	150
<b>Fuel Economy</b>	50
<b>Endurance</b>	350
<b>Total Points</b>	<b>1,000</b>

Figure 1: Formula SAE event points breakdown

## 1.1 *Static Events*

The Presentation event is a marketing presentation to a number of industry judges to evaluate the feasibility of a business plan based around the manufacturing of the vehicle. Aspects of this event include market opportunity, customer base, investment and production plans, and more.

Cost Analysis is a two part event. The first half involves evaluating the team vehicle for the quality of cost reporting. Prior to competition each team must compile a very detailed cost report encompassing every part, material, and labor time necessary to fabricate the car under full manufacturing conditions. These reports are then compared to the actual vehicle for accuracy of reporting, and then ranked based on overall price (with higher points being awarded to cheaper cars.) The second half of the Cost Analysis event involves the description of the manufacturing of a two items chosen at random from a list including: oil filter, brake caliper, lug/wheel nut, rear view mirror, electrical fuse, steering wheel, spherical rod end, or ignition coil.

Engineering Design is the most coveted of the static events because of its weight in the point distribution and also because of the prestige involved in being selected for Design Finals. During this event, the vehicle is evaluated by several industry judges to determine how well students used engineering principles to appropriately design, manufacture and incorporate parts or components for the target market. The judges during this event are very critical and examine everything from the bolt selection to frame layout to engine tuning. Judges may ask team members to justify any critical decisions and to also provide adequate background data for the decision. This is the area where well organized teams shine – the more engineering done prior to manufacturing, the more the result will be a cleanly produced, justifiable product.

## **1.2 *Dynamic Events***

Before teams can even compete in dynamic events, they must first pass a series of tests to determine the safety and compliance of the vehicles. The first hurdle is Tech Inspection. A number of judges will check the car from front to rear to make sure that each aspect of the vehicle falls within the envelope of the rules. If at any point a part fails the inspection, the team must return to their paddock to fix the part. Because the cars are inspected so thoroughly and because each car changes a great deal each year, there are often times when it will take multiple tries to get through Tech, which may consume an entire day of the event. The second inspection is Tilt Table, where the vehicle is tilted to an angle of 60 degrees to ensure that the vehicle will not roll over in the equivalent of a 1.7g maneuver, and also that no fluids will leak out of any component. Noise is the third inspection, when the vehicle muffler is checked for proper sound damping. According to the rules, the vehicle must not be more than 110 dBA at an average piston speed of 3000 ft/sec. The final inspection before the car is cleared for dynamic events is Brake Test, in which the vehicle must lock up all four wheels after a short acceleration.

Acceleration is a simple two-heat event to determine the vehicle's acceleration time over a flat, 75 meter distance. Each driver participates in one heat and gets two runs, creating a total of four acceleration runs for each team. Skid Pad is an event used to determine the lateral grip of the vehicle during a constant radius turn. The layout is a figure 8, as indicated by Figure 2. There are again, two separate heats, with two separate drivers with two runs each.

Autocross is set up as a short course (either defined by cones or in some cases laid out on racetracks) to determine the maneuverability and handling without direct wheel to wheel racing. Each car gets two heats, with two runs per heat. Each run consists of a single lap around the track. Running order is usually

sequenced by the acceleration times so that cars run with others with similar times, reducing the potential for overtaking or interference from other cars on a lap.

Endurance and fuel economy are the most important events of the competition, and both are run simultaneously. The event consists of a 22km race designed to test the reliability and performance of the team's vehicle. At the midpoint of the race there is a driver change and evaluation by track judges to ensure that there are no problems with the vehicle. Cars may be taken out of the race at any time due to malfunctions, leakages, slow times, or significant driver errors. Cars can also be taken out during the driver change period if judges determine that there are significant issues with the vehicle, or if teams cannot restart their cars. Teams are not allowed to work on their vehicle at all during the entirety of the event, so cars must make it through the entire race without external aid. The fuel is measured at the start of the race and at the end, and the score is determined by the average economy obtained during the event.

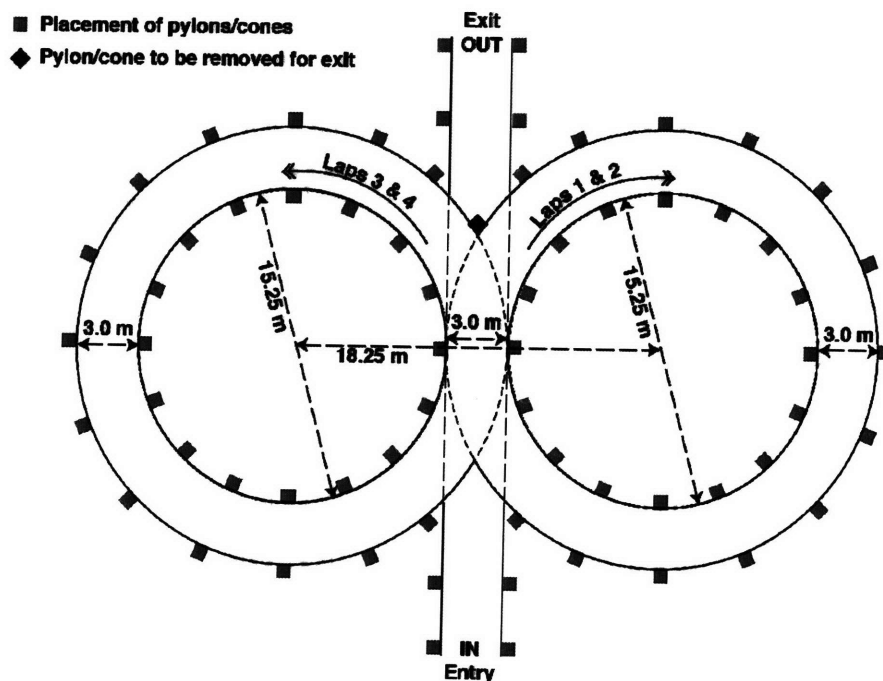


Figure 2: Layout of the Skid Pad event

## 2.0 Main Design Criteria

The construction of a Formula SAE chassis begins with a clear definition of the design's main goals. In the case of the vehicle frame, the main design criteria encompass four particular areas:

- 1) Rule compliance
- 2) Torsional stiffness
- 3) Weight
- 4) Component mounting and packaging.

These four areas represent the main criteria for evaluating a Formula SAE frame design and provide metrics for determining areas of improvement.

### 2.1 Rule Compliance

The framework for design specifications is dictated by a set of strict rules established by the Society of Automotive Engineers. These rules are in place to provide baseline requirements and restrictions to promote a safe engineering and testing environment. Nearly every component has a set of requirements that are checked during competition and the frame and chassis are no exception. In fact, because of the importance of the frame as a form of driver protection, these are some of the most diligently checked parameters during an inspection. Later in this paper I discuss specific material and geometry selections; this section is primarily to provide an overview of the safety framework the rules provide.

The primary vehicle structure must consist of the following components: a braced front roll hoop, a braced main roll hoop, a braced front bulkhead, two side impact structures, and an impact attenuator.

These components, along with the bracing that connects them, will offer the driver adequate protection in case of a catastrophic failure of the vehicle.

The rules specify baseline requirements for material selection and tubing characteristics: the primary structures must be fabricated out of round, mild or alloy, steel tubing (minimum 0.1% carbon) of the minimum dimensions specified in the following table:

ITEM or APPLICATION	OUTSIDE DIAMETER x WALL THICKNESS
Main & Front Hoops, Shoulder Harness Mounting Bar	1.0 inch (25.4 mm) x 0.095 inch (2.4 mm) or 25.0 mm x 2.50 mm metric
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver's Restraint Harness Attachment (except as noted above)	1.0 inch (25.4 mm) x 0.065 inch (1.65 mm) or 25.0 mm x 1.75 mm metric or 25.4 mm x 1.60 mm metric
Front Bulkhead Support	1.0 inch (25.4 mm) x 0.049 inch (1.25 mm) or 25.0 mm x 1.5 mm metric or 26.0 mm x 1.2 mm metric

**Figure 3: The minimum diameter and wall thicknesses for primary structure components.**

While there are other alternative materials (such as aluminum or titanium) and equivalent rules, the main roll hoop and bracing must be made from steel. These wall thicknesses are checked during competition through inspection holes. There are also geometric restrictions on the position of the various parts of the primary structure. Figure 4 and Figure 5 offer some examples of these required geometries.

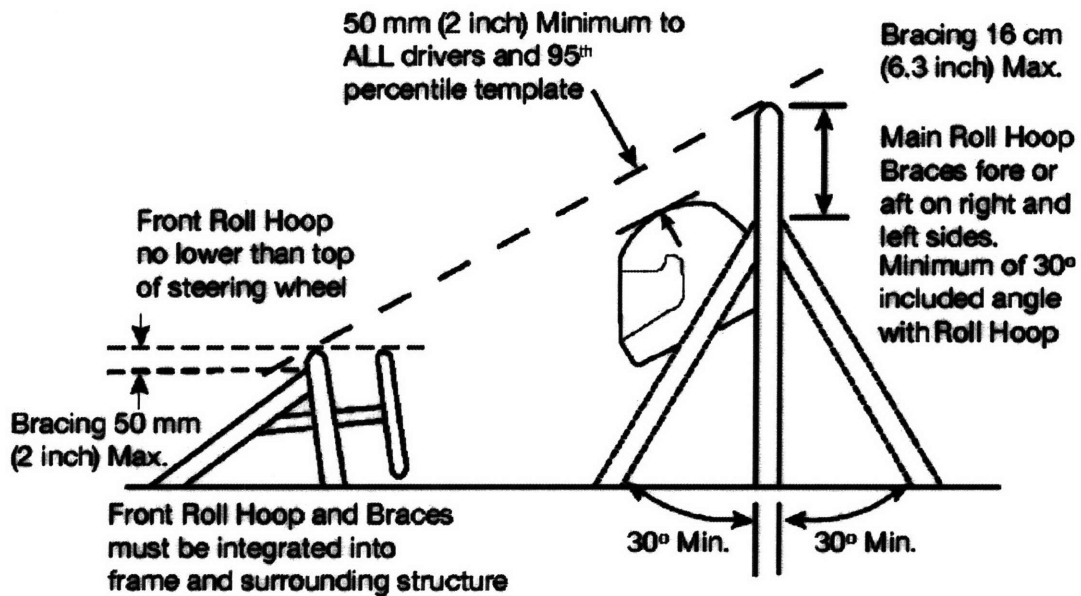


Figure 4: Regulations related to the front and main roll hoops and bracing.

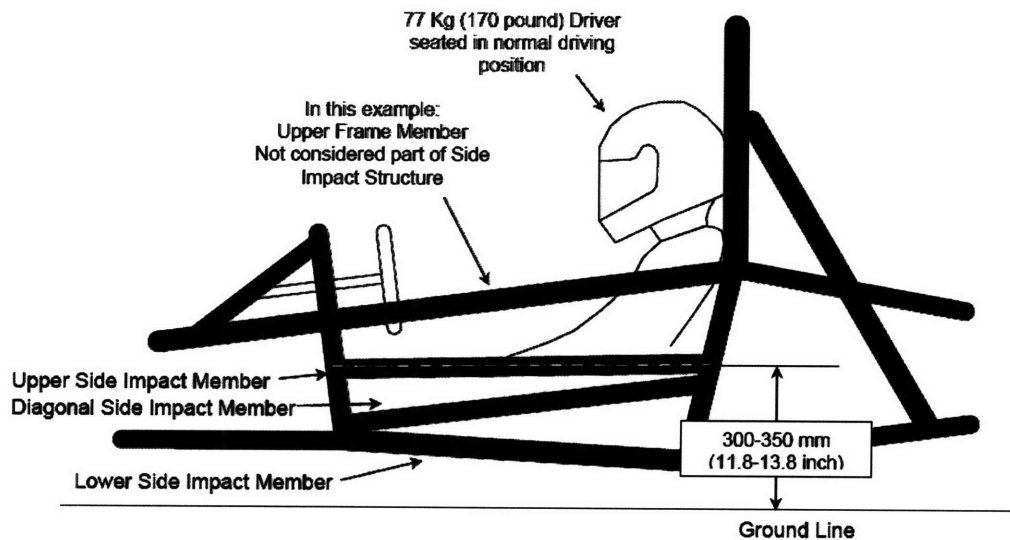


Figure 5: Required geometry for side impact bracing.

These restrictions are checked using standardized templates meant to represent a 95<sup>th</sup> percentile male driver. The material and geometric compliance dictated by the rules for the vehicular primary structure

form the majority of restriction in design. Even though there are the necessary geometries, there is still a great deal of flexibility in the unique frame design and through optimization and clever engineering it is possible to develop a great deal of differentiation.

Besides the tubular structures required by the rules, there is also an impact attenuator that is specified as “a deformable, energy absorbing device located forward of the Front Bulkhead.” This device must be shown to provide an average deceleration of less than 20 g for a 300 kg vehicle run into an impact barrier at 7 m/s. This property is demonstrated through analysis of the selected material, and submitted in a paper to an SAE representative prior to the competition for review. Teams may use any material that they find to fulfill these requirements, although many teams are moving towards aluminum honeycomb or crushable foams. Appendix 8.2 contains the submitted report.

## *2.2 Torsional Stiffness*

The torsional stiffness of a vehicle chassis is very important for its drivability. Because predictable handling of a vehicle is a function of both the suspension kinematics and the overall dynamic characteristics of the chassis, it is in the engineer and driver’s best interest to produce a very stiff frame. By incorporating a very torsionally rigid frame, the engineer allows the suspension characteristics to control a greater portion of the vehicle handling by eliminating as much flex and unpredictability, particularly in the response frequency in a complex frame as a result driving loads.

Because of the complicated nature of performing an analysis on what is essentially a collection of beams and trusses, it is often necessary to perform finite element analysis (FEA) on a model to determine baseline torsional stiffness and iterate from there to optimize the design. Typically, a more abstract way

of looking at the design is to try to predict load paths through the frame (from suspension loads) and make sure paths lead into nodes with significant triangulation. It is a good idea to look at extreme deformation models of the frame to determine problem areas, and to add bracing to decrease flexing in those areas. Additionally, it is often possible to utilize ultra-stiff parts of the frame such as the engine or the roll hoops as load paths themselves. This will often eliminate the need for extra tubing and weight, and simplify the design while adding significant stiffness.

From the three years of design experience that I have had in torsional stiffness analysis, a safe bet for a baseline goal is 2000 ft. lb. / degree of twist. That is, if you locked out the front and rear suspensions with rigid linkages, and loaded the front hubs with weight and had the rear attached to a rigid base you would experience one degree of twist in the chassis with a moment load of 2000 ft. lbs (calculated based on the distance away from roll center to the hubs).

Although it is possible to get much higher torsional stiffness values through the addition of more bracing and usage of alternative materials, (carbon fiber monocoques) this 2000 ft. lb. / degree is an acceptable amount, especially with the suspension we currently employ.

### **2.3 Weight**

One of the greatest challenges for a modern Formula SAE chassis designer is determining the appropriate balance between torsional stiffness and weight. Although torsional stiffness can be significantly increased with the addition of extra bracing or supports, these come at the price of extra material. For a race car driver, there can be no worse enemy than extra weight. It can mean sluggish acceleration times, longer braking distances, a taller center of gravity, and extra chassis roll in corners.

Added up, the extra weight can quickly eliminate any gains in stiffness. In the world of weight shaving, the racecar community is second only to aerospace in the struggle to save fractions of a pound. To this end, there must be an optimization and tradeoff between weight and torsional stiffness. The ideal case is the situation where the frame has been designed to be as stiff as it possibly can while utilizing as little material as possible.

Competitive Formula SAE racecars typically weigh between 400 and 500 pounds. The MIT Motorsports MY2007 racecar had a wet weight of 432 pounds. In order to achieve this light weight, the frame of the vehicle was only 54 pounds, including all mounting tabs and powder coat. Future frame designers should use this as a benchmark; a tubular spaceframe chassis with a similar torsional rigidity should not need to weigh more than 60 pounds, with proper and efficient triangulation.

## ***2.4 Component Mounting and Packaging***

The final and most influential design criterion for the frame is the importance of mounting and packaging the rest of the components critical to a racecar. Some parts will dictate how the frame geometry is changed, while other parts will adjust according to the frame design. In many cases, the specific racecar's style is an evolution of each of the previous years, focusing on iteration to optimize and adjust component mounting according to feedback on older vehicles.

The suspension is the component with the most influence on the frame geometry because suspension design is critical to the drivability of the vehicle. Placement of the suspension arm links can influence a great many aspects including the roll center, camber, and overall performance under acceleration, braking, and turning. This design is, in itself, an art form with a nearly limitless amount of variation to

achieve different results. In terms of Formula SAE racecar development, the frame design becomes secondary to the suspension geometry, and will often be modified to conform to the requirements set forth by the suspension kinematics designer. This is one case in which the frame geometry is significantly dictated by another design. Hopefully, after several years of experimentation and variation, a general geometry should be set and only slight modifications are required to improve performance. This way, extreme or drastic changes to both the suspension and frame geometry are limited.

Another important component that must be directly integrated into the frame is the engine. Besides the driver, it is the heaviest single component attached to the vehicle, and it is in the designer's best interest to get it as low to the ground as possible, and also to ensure an optimal fore-aft weight distribution. (50-50 is a good starting value, but the team has been recently aiming for a 55-45 rear bias to get more power to the drive wheels). In addition, the engine can be used quite effectively as a loaded structure because of its stiffness as a block of aluminum. By finding appropriate mounting points on the engine and using it to carry both suspension loads and drivetrain loads, it can greatly increase the amount of stiffness in the frame and decrease the amount of necessary tubing and bracing.

The majority of the rest of the components have mounting determined after the frame has been designed. These include: intake, cooling, oiling, fueling, electronics, seat, steering, pneumatic shifting, pedal box, and body. (Please see Appendix 8.1 for a summary of overall vehicle components). In all cases, there is close collaboration required between the frame designer and other engineers to determine if there are any critical dimensions that need to be incorporated into the frame. It also highlights the importance of the frame as one of the first components to be fully designed and completed.

## 3.0 Design Process

### 3.1 Material Selection and Cost

By far, the most common material used for Formula SAE racecar frames is 4130 chromoly steel.

Chromoly is the terminology used for chromium-molybdenum, which is an alloy of steel which, in addition to iron, is composed of 0.28-0.3% carbon, 0.8-1.1% chromium, 0.4-0.6% manganese, 0.15-0.25% molybdenum and 0.15-0.35% silicon. Compared to another low carbon steel alloy, 1020, the 4130 chromoly exhibits significant advantages in ultimate tensile strength (670 MPa vs. 380 MPa). Compared to aluminum (6061-T6), the 4130 chromoly exhibits similar advantages in ultimate tensile strength (670 MPa vs. 310 MPa) as well as shear modulus (80 GPa vs. 26 GPa) and comparable malleability at the cost of being heavier (.284 lb/in<sup>3</sup> vs. .0975 lb/in<sup>3</sup>). Furthermore, 4130 is very easily welded with either TIG or MIG, and does not generally need heat treating of the welds for wall thicknesses below .095 inches. Since the main roll hoop and bracing must be made from steel, it is simple to directly incorporate the rest of the tubes into that primary structure without having to worry about failure points at special mounting brackets, etc. Additionally, since the material is used for many of the other components on the vehicle mounting tabs can be easily waterjetted and welded directly onto the frame.

Two major distributors are used for the majority of round tubing: The Chassis Shop and Aircraft Spruce. They have an excellent selection of round tubing and square tubing in a wide variety of diameters and wall thicknesses. A typical 1in. diameter .035" wall thickness piece of tubing will cost about 24 cents per inch. Tubing is shipped in 8 ft or shorter sections, and for economical reasons it is obvious that purchasing all the material at once is ideal. For the current MY2008 vehicle, the purchase and pricing for the initial shipment is shown in the following table:

<b>Tubing</b>	<b>Type</b>	<b>Amt. (ft)</b>	<b>Price per ft. (Aircraft Spruce)</b>	<b>Total Price (\$)</b>
1" - 0.095"	round	16	4.70	<b>75.20</b>
1" - 0.065"	round	16	3.25	<b>52.00</b>
1" - 0.049"	round	16	3.20	<b>51.20</b>
1" - 0.035"	round	36	2.80	<b>100.80</b>
5/8" - 0.035"	round	19	2.45	<b>46.55</b>
1"x1" - 0.049"	square	8	7.25	<b>58.00</b>
<b>TOTAL</b>				<b>383.75</b>

**Figure 6: Initial purchase of raw materials for MY2008**

These prices are indicative of only the initial raw amount, and do not include the shipping (which is a significant portion of cost).

### **3.2 Use of Solidworks and CAD**

Computer Aided Design (CAD) software is absolutely essential for a competitive Formula SAE chassis design. The computer allows the design engineer infinite flexibility and variation at a fraction of the cost of creating mockups. With proper time and analysis, a designer can quickly go through many iterations of a particular design and incorporate them easily with other models for components other team members are working on. Additionally, the models created within CAD programs are often easily transferable to machine tools that can use the code directly. This is especially helpful when designing parts that need to be waterjetted, machined on CNC mills or lathes, or cut on 5-axis laser cutting machines. Specifically for the frame, CAD enables the designer to break out each individual frame tube for analysis, iteration, and manufacturing. If enough of the design has been properly completed in CAD, the actual fabrication does not need to take longer than a week.

At MIT, the Mechanical Engineering Department provides unrestricted access to a recent copy of Solidworks, a relatively low cost and popular mid-range CAD package. For MY2008, Solidworks 2007 was used for the majority of design of the frame and other components. Other competing CAD packages include Pro/Engineer and CATIA.

The process for modeling a single tube in Solidworks is relatively simple. By using the weldments structural member feature, it is possible to quickly and simply create a model of a tube, and trim connecting tubes to fit precisely onto each other. The first step is to add the specific profiles of the tubes being used; these are the cross sectional drawings of tubes (ie, a 1 inch diameter circle with a .035 inch wall thickness). Then, the centerline of the tube can be sketched in Solidworks. Then by using the weldments tool, the profile can be extended to create a 3D model of the tube with the appropriate diameter, wall thickness, and geometry. Then, if there are two intersecting tubes, the end profiles can be trimmed appropriately to remove excess material and provide a clean fishmouth for jiggling. Figure 7 and Figure 8 summarize the process in Solidworks of trimming and fishmouthing tubes.

Complexity in this procedure arises due to the sheer number of different structural elements, and the motivation to correctly dimension and define tubes to maintain the flexibility of the model if you need to change parameters. For instance, if the suspension point needs to move inboard by 1 inch on each side, the designer would like to retain the flexibility to make this change without extensive modification of the entire model. In this vein, tube relations must be defined appropriately off of each other to take advantage of the ability of the CAD model to update itself as parameters are changed.

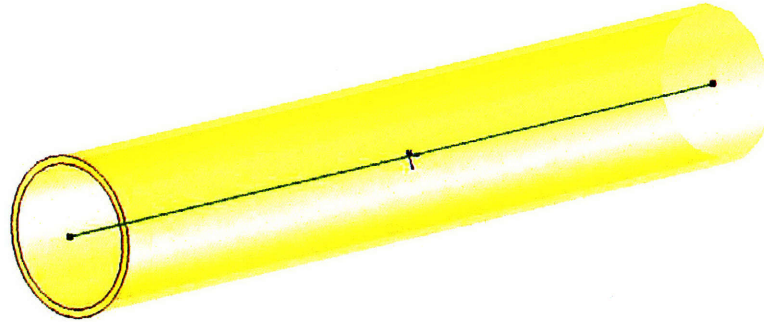


Figure 7: A simple weldment tube (note the profile and the sketch centerline).

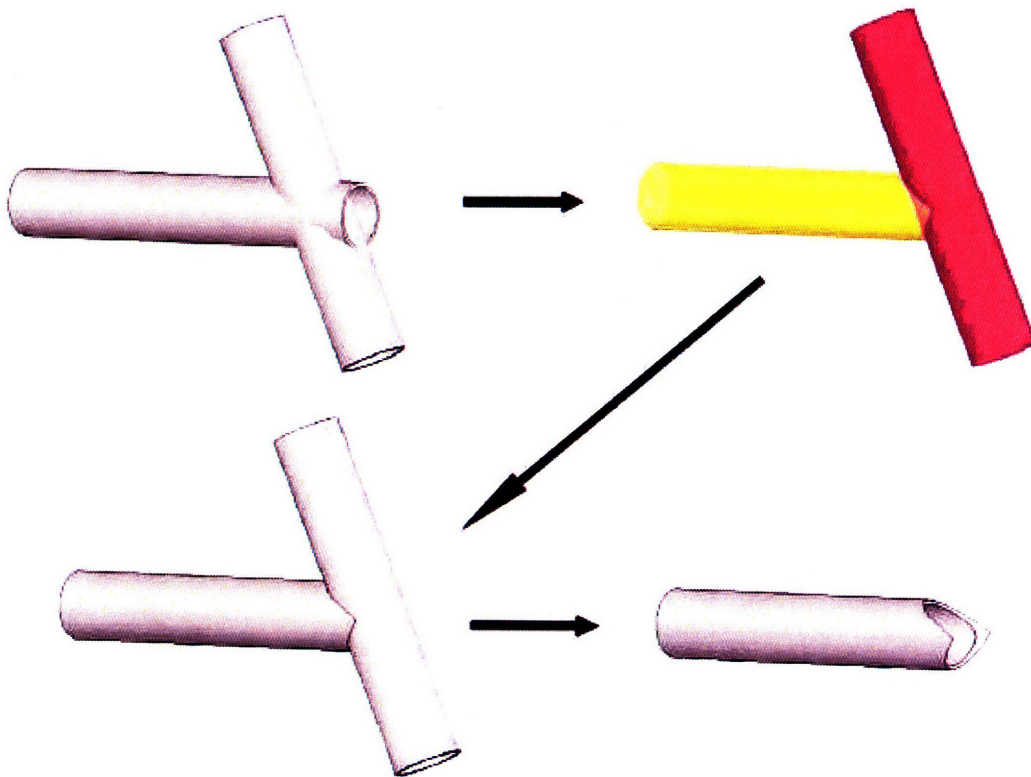
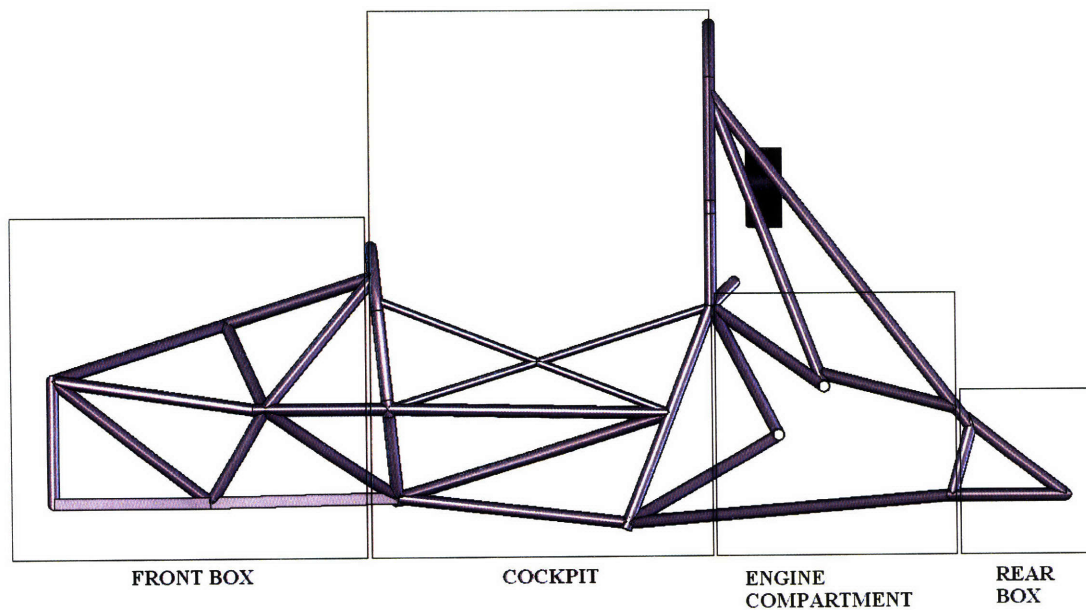


Figure 8: An example of the trimming procedure to create proper end profiles for fitting.

### 3.3 Frame Breakdown and Description

When beginning the initial design of the frame it should be broken down into several specific areas. This simplification is important for maintaining sanity during design and is also very helpful during fabrication.

There are 4 major sections of the frame: the front box, the cockpit, the engine compartment, and the rear box. Figure 9 illustrates these different sections within the frame. The front box is defined as any structural tubing from the front roll hoop, forward to the front bulkhead. The cockpit is defined as the area where the driver sits and consists of tubing from between the front roll hoop and the main roll hoop (including side impact bracing and seatbelt bracings). The engine compartment is where the engine mounts into the frame from the main roll hoop. The rear box is where the rear suspension points mount, and where parts of the drivetrain, including differential brackets and rear engine bracing are mounted.



**Figure 9: Breakdown of the frame design into sections to simplify design: front box, cockpit, engine compartment, and rear box.**

To further break down the frame, each section is defined by a few particular parameters, and a great deal of the remaining structural members simply link nodes together. In the front box, perhaps the most complicated of all the sections, the geometry is defined by the front bulkhead, the suspension mounting points, and the front roll hoop. The front suspension points are mounted on four main tubes running fore-aft. The bottom plane of the car is constructed from square tubing because of the geometries of the pedal box and its ability to slide back and forth to accommodate different driver heights.

For the cockpit, the majority of the side impact bracing and connecting geometries are simply linking the front roll hoop and the main roll hoop. The key to proper design is making sure to conform to the specific rules regarding material and tubing selection, and proper sizing of the cockpit based on driver size.

The engine compartment tubes are based on the location of the engine. In recent years the engine has been lowered significantly to take advantage of a dry sump system, which eliminates the need for a large oil reservoir at the bottom of the engine. Tubes extend from the main roll hoop back to 4 mounting points on the engine and are triangulated for strength and rigidity.

The rear box has been significantly simplified from previous years. Because of the use of a trailing arm rear suspension design, the suspension points have been made as compact as possible. This increases stiffness and directs loads into the engine block. In future years, it may be possible to eliminate the use of the rear box entirely, and modify the rear of the engine block for mounting. An important additional set of members to note is the main roll hoop bracing which extends from the top of the main hoop to the back of the rear box, and the bottom runners that tie in the bottom of the main roll hoop.

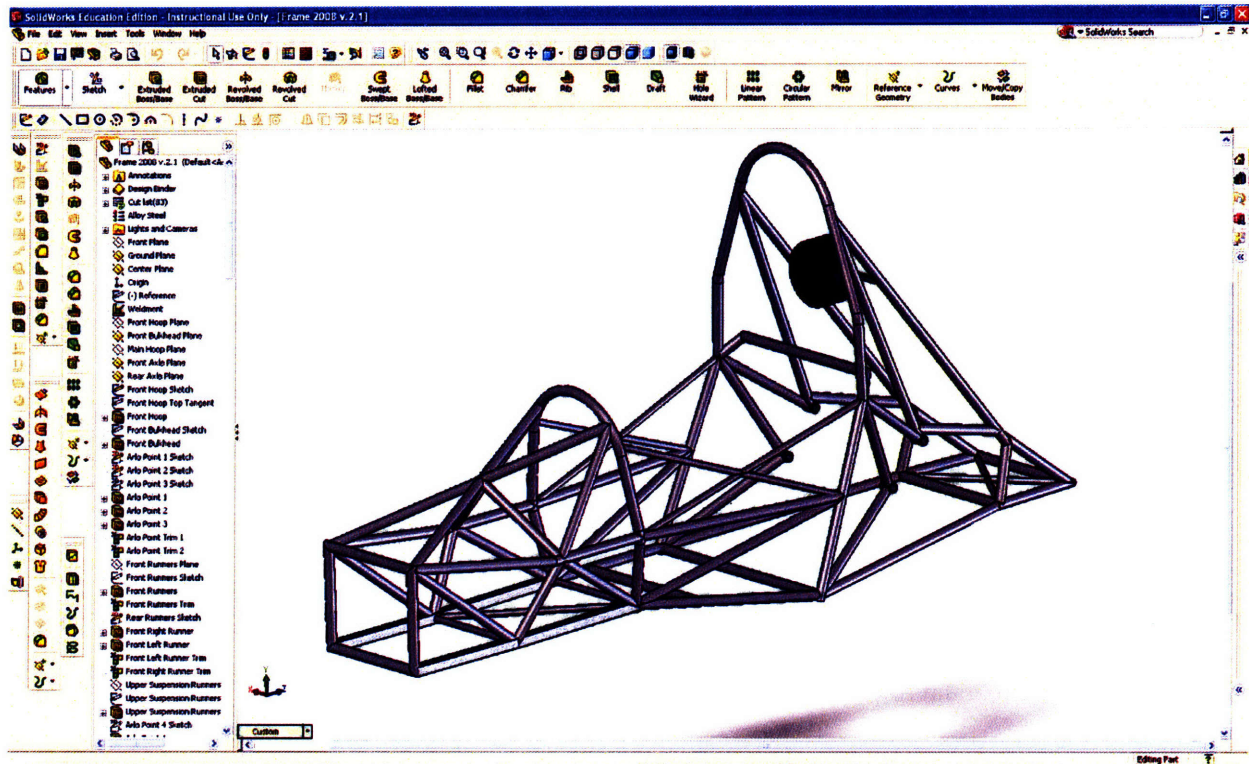


Figure 10: Screenshot of frame iteration in Solidworks 2007.

### 3.4 FEA Optimization and Iteration

One of the advantages of Solidworks 2007 (over other editions of Solidworks) is the ability to use its sister program, Cosmosworks, as an FEA tool for beam element analysis. Although Cosmosworks was previously available, it did not have the ability to properly mesh and solve each structural tube. Cosmosworks 2007, however, is now capable of taking a weldment and converting the structural members into beam elements.

Theoretically this program should be able to fully analyze the Formula SAE frame. However, due to lack of experience with the FEA characteristics of this system it was difficult to get a deterministic result. Part of the problem with running this simulation is the computing power needed – ideally the analysis requires significant CPU and memory so that it does not crash. Because of lack of access to such a high

powered computer at the time of development, it was difficult to perform enough iterations to properly determine the constraints and loading characteristics necessary. It was also difficult to model the attachment points and solid block characteristics of the engine as desired.

Future frame engineers should focus a great deal of time and resources on perfecting the use of Cosmosworks to perform FEA analysis, especially since it is able to analyze specific stresses and forces in each beam element. This could be very useful in the verification stage by using strain gauges applied to the corresponding frame members.

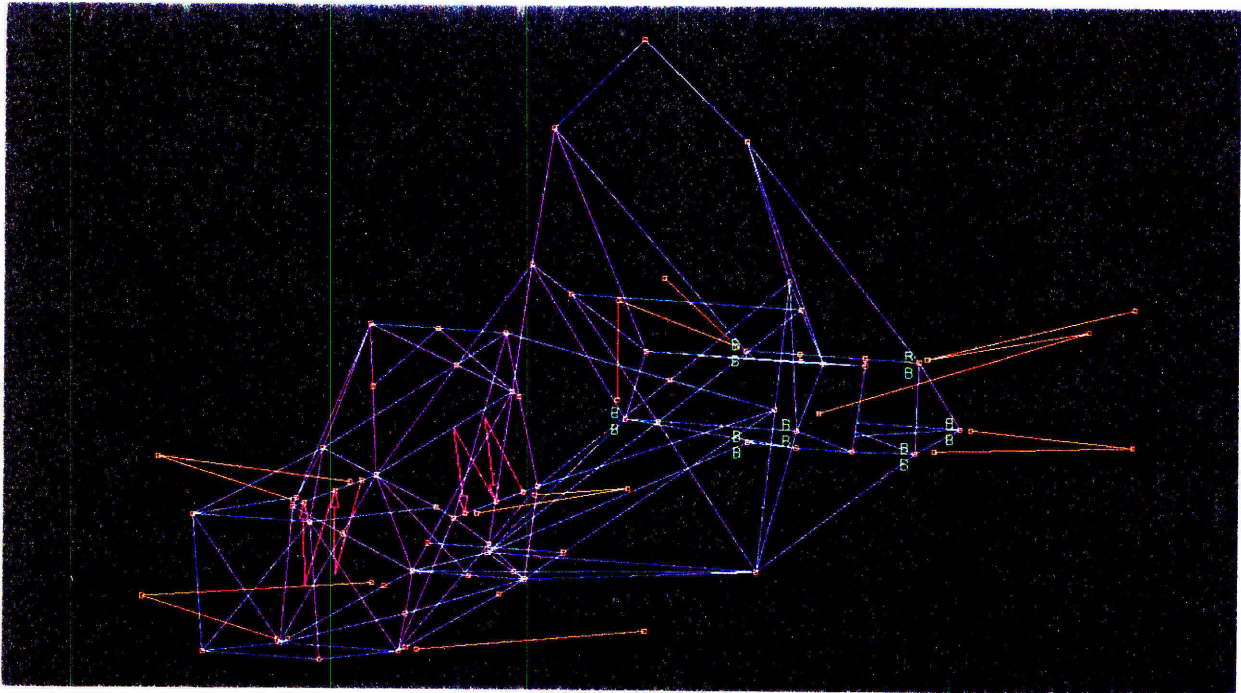
An alternative program successfully used in the past to analyze the frame is Adina. It produces results based on nodes in the frame, and simulates beam elements between them. For the MY2008 simulation the nodes were modified according to the CAD design in Solidworks and then frame elements were added between them. Loading characteristics were developed in conjunction with the suspension model to determine the reaction forces at the suspension mounting points. These reaction forces are then inputted into the Adina model, and the simulation is run. Figure 11 shows a screenshot of the frame before simulation. It is possible to see the geometric location of the suspension, as well as the loading on the front suspension mounts and the restraining characteristics on the rear. A further improvement to this model would also simulate loading through the rocker mounting and shock mounts into the frame.

After the simulation is run, it is possible to measure the deflection of a specific point from the original condition. A point is chosen in the front box, and the deflection measured corresponds to a certain amount of rotation due to the loading. This value can then be extrapolated out to determine the torsional rigidity of the frame in ft. lb/degree. The process can be reversed, and the front suspension can

be constrained and the rear loaded as a test to verify the torsional rigidity value. Figure 12 shows one of the possible results from the analysis: an axial force plot for beam elements. For a loading of 1000 lb. total (500lb. up on one hub and 500lb. down on the other hub) the torsional rigidity figures were: 2284 ft. lb/degree front loading and 1887 ft. lb/degree rear loading. This puts the frame within a desirable amount of torsional rigidity.

Further experimentation with substitution of geometries and frame tube characteristics would probably yield higher values. Two goals of the future designer should be to:

- 1) Improve the simulation by using more advanced software such as Cosmoworks and improving the suspension loading model
- 2) Performing much iteration to optimize the frame stiffness.



**Figure 11: Adina model of frame, suspension and loading characteristics.**

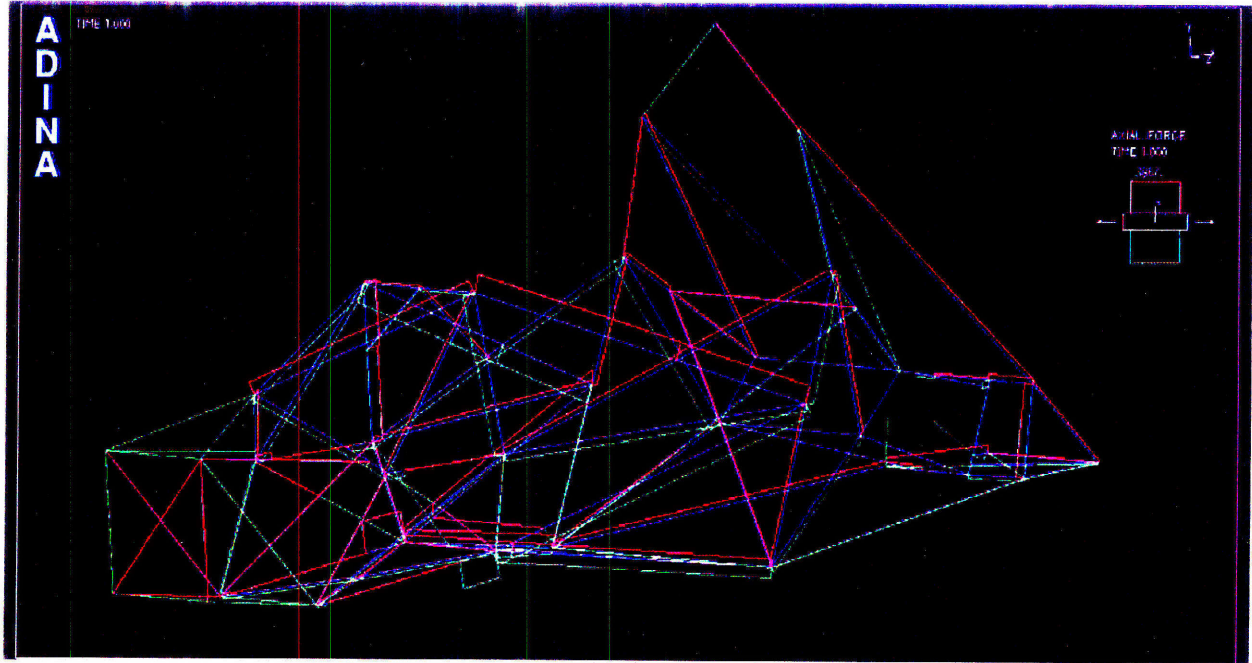


Figure 12: Adina model showing axial loads through frame members.

## **4.0 Manufacturing**

### **4.1 Scheduling**

Scheduling the production of the Formula SAE vehicle is the most difficult part of preparation for the annual competitions. In 2008, the schedule is even tighter with an additional competition happening in mid-April at the Virginia International Raceway, a month earlier than the traditional race in Michigan in May. Because of this accelerated schedule, a successful build is hinged on a well laid-out plan that leaves enough time for proper design, manufacturing, assembly, and testing.

An important aspect to take into account is the presence of the MIT academic school year as a major influence on scheduling. Because MIT Motorsports is an extracurricular club organization, it presents unique challenges to its members. One issue is that the school year starts and ends in September and May, which limits the time in which most team members are present on campus and available for work. Although fabrication can begin during the summer months before September, it is difficult to guarantee that there is enough manpower consistently available to achieve desired milestones. Another limitation is that many members graduate every year in May, and these members are often the most experienced seniors on the team. At the same time, many new members arrive every September who are often inexperienced with detailed engineering and manufacturing, but can provide significant manpower to help in vehicle construction. One of the other unique aspects of MIT's schedule is the existence of the Independent Activities Period (IAP) during January, where students do not always have formal classes, and can use the free time to work heavily on vehicle fabrication. It is during this period that most of the manufacturing for the rest of the components during the build process should occur.

Because of the frame's importance as the base for all vehicle components, it becomes the highest priority on the build list. In many cases component design cannot even be started until the frame is finalized. For this reason, design of the frame should be completed as early as possible, with a final version completed at the very latest by the start of the school year in September. This will allow the other student engineers time to regroup on campus in the fall to organize a plan for the design of the rest of the vehicle components without having to wait for a finalized frame. What this means is that there needs to be heavy collaboration between the frame designer and the suspension designer to finalize their models. This also allows fabrication of both the frame and suspension to begin as soon as possible, and allows for the utilization of new members to train them in basic fabrication techniques.

## ***4.2 Laser Cutting Tube Profiles***

One of the most valuable tools that the MIT Motorsports team has implemented this year is the outsourcing of tube preparation to a laser cutting service. Maley Lasers, located in Cranston, RI, was given the task of using their 5-axis laser cutting machine to prepare a majority of the round tubing for the frame. There were several reasons for this decision: the first and most important was the acceleration in schedule and the necessity of having the vehicle done in April, rather than May. The second was the desire to move towards a more realistic method of fabrication.

Prior to laser cutting, tubes were prepared manually by team members. In most cases, a 3-axis Bridgeport mill and 1 inch hole saw was used to fishmouth the ends of tubes. However, as frame geometries became more complex it was apparent that this technique took too long and was not reliable. In many cases because of the complexity of the profiles each tube had to be manually ground to fit using a bench grinder, and each tube could take many hours, especially if it was accidentally ground

too short and the process had to start again. The decision to move to a laser cutter would thus save a great deal of time and frustrations during fabrication, provide a much cleaner joint for our welders, and ultimately provide a much stronger structure. It was hoped that by frontloading the work and focusing on a comprehensive CAD model, there would be little to no modification of tubes necessary.

The process of ordering tubes to get laser cut is fairly simple. Because a new model is made in Solidworks using weldments, the CAD program allows the engineer to select each individual structural member and export it as a file. Since each of the tubes is trimmed properly to interface with other tubes, the individual part files contain the tube exactly as it needs to look and fit in the final vehicle. The 5-axis laser cutter works in a similar way to a CNC mill or lathe. One simple way to think about it is to visualize the tube as being “unrolled,” with the length of the tube becoming the X axis, and the unfurled profile lying along the Y axis. This flat sheet and the subsequent end profile is what the machine sees using programmed code; but instead of the X and Y axes being in plane with each other, the X axis defines longitudinal movement, and the Y axis becomes wrapped around the tube again. Now the laser cutter can move around the cylinder of the tube and cut out the appropriate profile.

There are a few advantages and disadvantages to this process. First of all, the service can sometimes be expensive, depending on the complexity and volume of cuts that need to be made. This is because the initial setup is quite costly. The most time consuming and technically demanding part of the process is writing the code for the machine, and it is important to setup the machine properly. However, this is advantageous because if a tube ever needs to be remade, the cost of production is relatively low. This makes it enticing to get two sets of frame tubes cut, and introduces the possibility of making a few frames for testing (given, of course, an adequate amount of money, materials and time). Additionally, as

indicated above, the team also provides the raw materials for the operation and must front the cost of both tubing and cutting.

This extra cost pays off, however. By establishing a sponsorship option with Maley Lasers, it was possible to get a significant amount of the original quote (\$3000) subsidized to \$1000. The bigger savings occurred in the fabrication. Over the course of one week in IAP the frame was nearly 98% complete, with only a few customizations needed. Any mistakes where tubes needed to be recut were due to errors in the initial dimensioning of the tubing in the CAD model; with more experience it is estimated that future frames will be fully fabricated in only a few days. This is compared to the previous fabrication time of a month and a half. Because of the extra amount of time spent working out the details of the initial deal (finding and negotiating sponsorship options) the cutting was pushed back to the winter. However, in future years this should happen as soon as frame design is finished, and final fabrication should be done well before December. Unquestionably, the laser cutting services provided by Maley Lasers were indispensable in reaching the goal of shaving an entire month off of the vehicle production schedule.

### **4.3 *Bending Roll Hoops***

The laser cutting service is not able to provide preparation for every tube; certain complicated structures – mainly the roll hoops – possess complicated curves and bends which make it necessary to manufacture them in-house. The bends in the hoops are accomplished in two ways: the first with a custom made jig and heat aided bending using an oxy-acetylene torch, and the second with a tube bender and a 5 in. radius die for a 1 in. diameter round tube.

Because dies for tube benders are very expensive, it does not make sense to purchase a new set for every new design. Instead, special radius bends, such as those found in the tops of the front and main roll hoops, are accomplished by making jigs. In order to make this jig, a 1:1 scale drawing of a perpendicular view to the hoop is created in Solidworks. This is then printed on a plotter, and traced onto a piece of plywood. This plywood is then cut with a jigsaw. It is important to take into account a small amount of spring-back that will occur at the end of the bend. The edges of the profile are then covered with a thin piece of aluminum or steel to prevent burning of the wood from contact with the hot steel tubing.

The steel tubing is prepared by filling it with sand to prevent buckling during the extensive bending; judges at the competition check each bend to make sure that there are no wrinkles. The tubes are filled with sand by first tapering the ends so they are sharp, and then by pounding in a wooden plug. The tube is packed with sand, and the other end is plugged also. A small piece of square tubing is also welded onto the tubing at the end to help lock it into the bending jig and keep the bend in plane. A matching notch is cut out of the bending jig to accommodate this square piece.

The jig is bolted down to a large, flat granite table to provide stability during the bending. A strap is also present around the widest part of the bend to help hold it against the jig. The tube is heated to cherry red by a rosebud tipped oxy-acetylene torch, being careful to heat the tube uniformly. While still cherry red, the tube is placed flat on the table (making sure that the notch and square set piece are held securely and flatly by the strap) and the tube is pulled and bent along the jig. The hardest part of doing this is making sure that the bend stays in plane all the way around the bend, and that the person on the far end of the tube makes sure to **pull** the tube as he/she bends it around the jig. This helps to prevent any kinks or areas where the tube pushes out away from the radius of the bend. At the beginning it is a

good idea to bend small lengths at a time; as expertise and confidence increases, the amount of tube per bend will also increase.

For smaller, secondary bends, it is acceptable to use a manual, electric, or hydraulic tube bender to attain the desired profile. In these cases it is important to simply follow the directions on the machines, and to make sure that the bends are at the correct angle and are in the correct plane. Tweaking with heat is also used to perform small adjustments to make sure the bends are to spec. Figure 13 shows the main roll hoop jig with a freshly completed roll hoop after bending.



Figure 13: The main roll hoop jig and bent roll hoop

#### ***4.4 Jigging Frame Members***

The jigging of frame members can be as complicated and high tech as you want; it is important, however, to keep in mind that this vehicle is a one-off prototype that will probably change from year to year, and that there is a limited amount of time to fabricate the frame. In this situation it is ideal to utilize a method that allows for a decent amount of accuracy, with a maximum amount of flexibility and variability.

The traditional technique utilized by MIT Motorsports for the past few years has been to use a full size plot of the frame as a guide for the fabrication. A 1:1 scale plot of a top-view of the frame is printed out and taped down to a large piece of high quality wood. This base is then put onto a large, flat granite table. Because every frame line is visible on the plot, it is possible to measure directly to the lines using squares to verify that the frame members follow the correct geometries.

The best way to visualize the construction of the frame is similar to how it was broken up during the design. By focusing on the four different areas (front box, cockpit, engine compartment, and rear box) separately, it greatly simplifies and clarifies the construction. The front box is the most complicated of all, but can be made simpler by jigging specific structures first, and linking the rest of the bracing.

The most effective way to use the paper plot is in a plane. The front bulkhead, for instance, is a very simple piece to make. A full scale plot of a perpendicular view of the front bulkhead is made, and taped down to the plywood. Jigging pieces, or smaller pieces of 1 inch thick plywood, are screwed down with the flat sides touching the exterior lines of the frame members. This way, the tubes can be physically jammed between the blocks and will be held in the correct geometry. The next step is simply getting the

tubes to fit. In a simple, planar, rectangular geometry such as the front bulkhead, it is easy to grind 45 degree angles into the tubes at the correct lengths. These pieces are then placed into the jig, tacked, and then fully welded. This piece is then ready to be attached to the full frame. Figure 14 shows the setup used in this technique including: board, table, plot, and CAD model.

By carefully using the CAD model measurements, it is possible to line up nearly every critical part like this. After fabricating the structural components that are in plane with each other, they can be jugged up to each other in 3 dimensions using shims and carefully using a digital level to check against the model.

For the front box the fabrication order is:

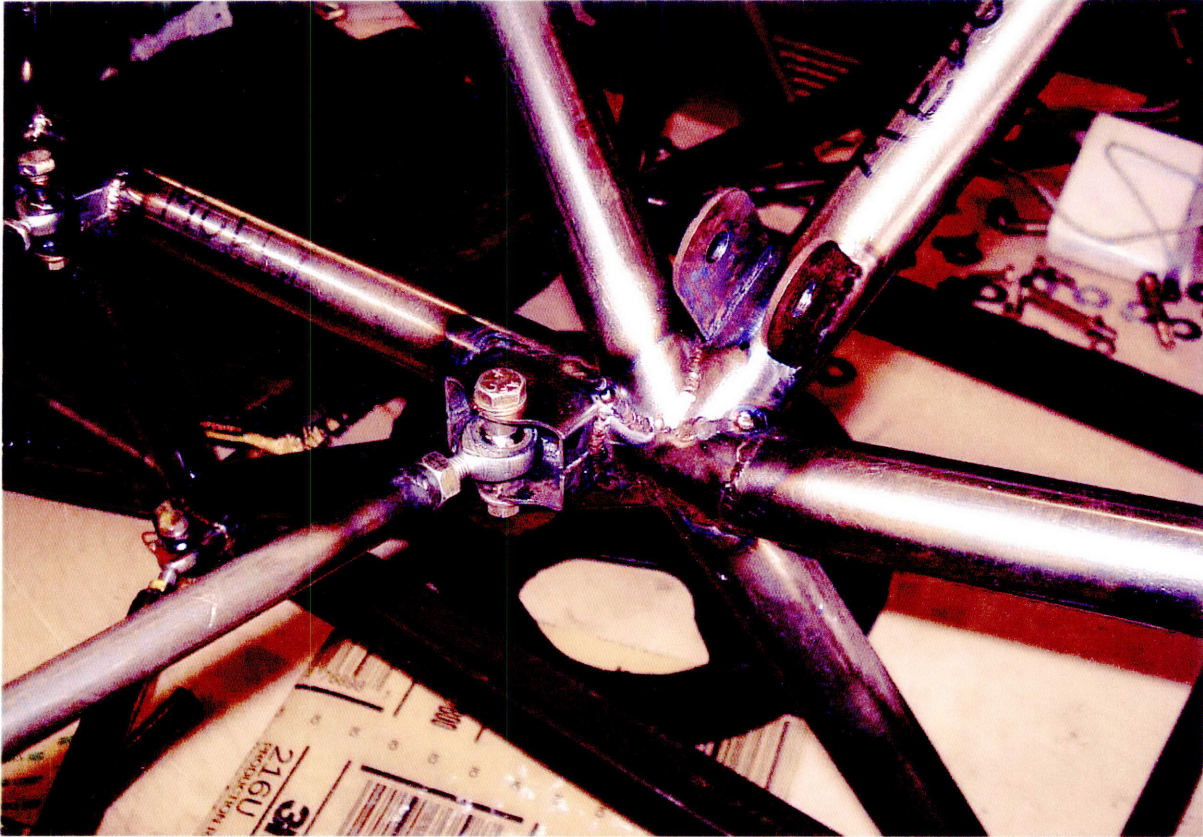
- 1) Front bulkhead
- 2) Bottom runners
- 3) Front roll hoop
- 4) Roll hoop bracing
- 5) Suspension runners
- 6) Finish bracing



**Figure 14: Jigging the front roll hoop on the frame plot**

The finish bracing is where the laser cut tubes are critical. Since these tubes can often be the most complicated, and are most important for linking nodes, they can literally drop into the right place and be tacked with very little additional preparation besides cleaning.

After the front box is completed, the rest of the cockpit can quickly be constructed. The important part is to jig the main roll hoop at the right angle and location, and the rest of the side impact bracing is easy to fit into place. Figure 15 shows a complicated joint that was easy to construct with the use of laser cut tube profiles.



**Figure 15: A complicated node of the frame.**

The engine is the next critical component that needs to be placed. A mockup engine is placed on the plot and aligned to the correct position as dictated by the model and desires of the powertrain division.

Then, engine mounts are fabricated; these are the pieces where the engine bolts go through the frame and screw directly into the engine block. These are fabricated from short, 2 inch long sections of .065 tubing with endcaps welded on. These are bolted to the engine with the appropriate spacers, and then the frame members are fitted from these engine mounts to the main roll hoop.

The rear box can be fabricated simultaneously to the rest of the frame so far. Again, using the same plotting and jiggling principles, the box can be jiggled and shimmed into the appropriate relative position

on the plot. Then, the main roll hoop bracing and the bottom runners are added to connect the rear box to the rest of the frame.

#### **4.5 *Welding Frame Members***

The majority of welding is done using a Tungsten Inert Gas (TIG) welder, also known as Gas Tungsten Arc Welding (GTAW). This type of welding uses a nonconsumable tungsten electrode to heat the material by using a constant current arc between the electrode and the working piece and by adding filler material. The arc and weld are protected from contamination by an inert gas such as argon, which is pumped out of the torch around the electrode.

When welding, the electrode provides a sharp, high temperature point that heats the material into a puddle. Filler material is added to the puddle and used to bridge any gaps between work pieces while the puddle is advanced along the seam. A foot control allows the welder to control the arc temperature and intensity, which can also be varied by the angle and distance of the electrode from the base material. Figure 16 diagrams the welding process and setup. For steel, the electrode uses DC current with straight polarity and a negatively charged electrode. Because the welding process emits UV radiation, it is necessary to wear protective eyewear and shielding to both see the weld and to protect the eyes and skin.

TIG welding is preferred to many other types of welding such as MIG or arc welding because of the extremely high quality welds due to the shielding gas and the limited amount of work heat it produces on the part. However, one of the drawbacks to this technique is speed; TIG welding is also one of the slowest methods and requires the most skill to perfect. Welding tacks is another important technique to

facilitate fabrication. Before laying a final bead, it is important to put two frame members together in the correct position and add to small bits of weld to hold them together. Proper tack welds help to prevent any pulling of the pieces due to the extreme heat produced during a final weld.

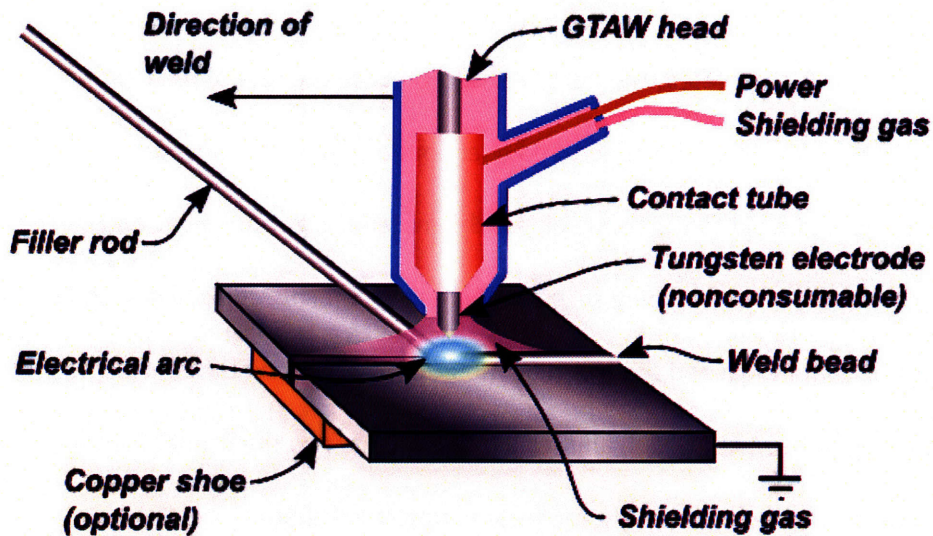


Figure 16: TIG / GTAW welding

One of the most important considerations in creating a high quality TIG weld (besides the skill of the welder) is the cleanliness of the part. To this end, it is important to clean pieces of steel through a variety of methods: removal of burrs, sand blasting, stainless steel brushing, and acetone. Any dirt, oil or other contaminants will lead to inconsistencies in the weld. Additionally, it is very important to provide breather holes for hot air to exit the piece. In a racecar frame this is especially important, since there are points during fabrication when some tubes end up with fully closed ends without breather holes. If this is the case, hot gas created from the weld can blast back up through the weld, blowing holes in the molten material and making a good bead impossible to form. Preferably, there are also no gaps between two pieces being joined together. However, this is sometimes not the case with manually ground parts.

Welders can often bridge gaps (unhappily) that are no wider than the filler rod they are using, but these welds are often weaker and more susceptible to failure. Overall, cleanliness and correct preparation of working pieces will lead to a happier and more content welder.

#### ***4.6 Mounting Additional Components***

Once the frame has been completed, the next task is to prepare the rest of the components that need to mount to it. The reason for this is the need to powder coat the frame for aesthetics. After being powder coated, it is impossible to weld to the frame unless the material is ground away and cleaned, which is undesirable. Most components including suspension, fueling, cooling, oiling, exhaust, seat, shifter, pedal box, and steering all require welded tabs for rigid mounting. At this point their designs should have been completed according to the CAD model, and should be optimized to the frame. Tabs and mounting brackets should be fabricated accordingly and welded onto the frame.

The most important of these components is the suspension. The hard mounting to the frame occurs through chassis brackets, which are fabricated from waterjetted pieces of 4130 steel plate that are bent and welded. These are aligned so that the bearings at the ends of the suspension A-arms can be bolted directly onto the frame. Additionally, there are many tabs that are required to mount rockers and suspension shocks. These tabs and jiggling are covered by the suspension designer.

#### ***4.7 Finishing***

Part of creating a clean vehicle design is in the final fit and finish of the frame. In order to provide an aesthetically pleasing look as well as a protective coating to prevent oxidation and rusting of the steel when exposed to the elements, a powder coat is commonly applied. Powder coating is different from

conventional liquid painting in that the binder and filler materials are not suspended in a liquid carrier; instead the powder is applied electro statically and then cured. The powder coating produces a number of desirable effects, both functional and aesthetic. The process usually creates a much harder and tougher finish that is more resistant to scratching and chipping than conventional liquid paints. Part of the reason for this is because of the physical process of heating, melting, and cooling the powder coat across the entire materials, allowing the powder coat to establish crosslinking as it cures. Because of the uniformity of the electro static powder spray, the consistency and final finish of the powder coat can be of a much higher quality than traditional paints. This means less overspray, almost no visible runs, and few differences in coat thickness or orientation. Powder coating is also extremely flexible in the number of choices and options for color and finish, from simple flat black, to glossy, colorful finishes.

One of the most important things that must be done to ensure a high quality powder coat is cleaning. Similar to welding, any oil, grease, dirt, oxidation, flaking, etc. must be removed prior to sending the frame to paint. By ensuring the surface finish is as clean as possible, it ensures that the powder application will be uniform and bond well to the surface. Ideally, a thorough sandblasting provides an effective surface for powder coating. Figure 17 and Figure 18 show the frame before and after a glossy black powder coating.

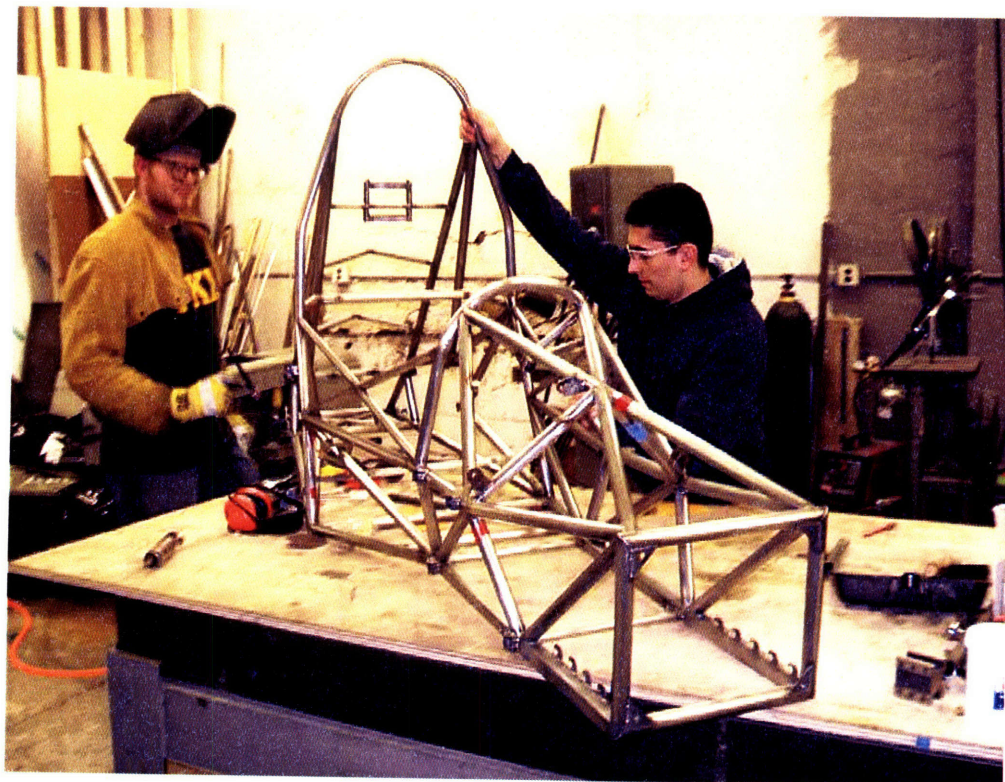


Figure 17: Frame cleaned and prepared before powder coating

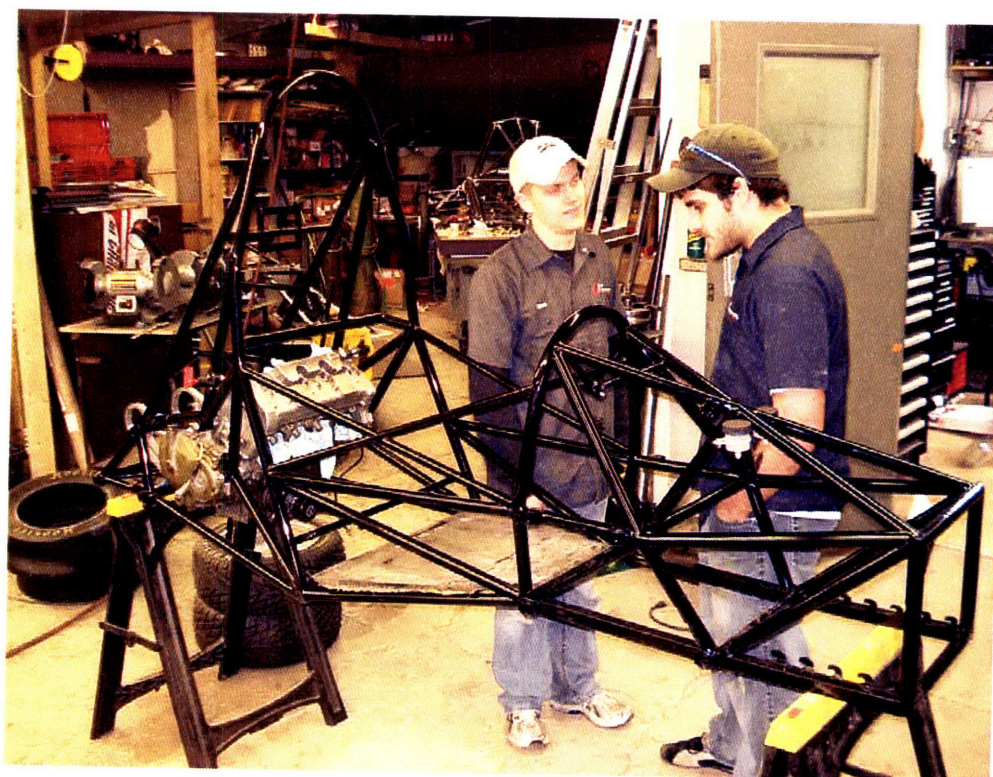


Figure 18: Completed frame with powder coat.

## 5.0 Verification

### 5.1 Torsion Testing

A torsion tester is constructed to perform a physical validation of the baseline torsional rigidity figures calculated from the FEA model of the frame. Ideally, the real world conditions will exactly mimic the simulated conditions. To this end, a torsion tester is designed to load the frame through a locked out suspension by rigidly constraining the rear and adding weight on a moment arm that is attached to the front hubs. A level is used to determine the amount of rotation for the weight added.

One interesting phenomenon that happened while testing the MY2007 vehicle was that a suspension component buckled when the torsion tester was loaded with a full load to simulate the conditions in the FEA model. What this indicates is that the limiting factor in the stiffness of the overall chassis was the suspension, and not the frame. In other words, the loading on the frame is not a realistic condition because the suspension would buckle before the frame showed enough deflection to cause significant unpredictability in handling. It is also indicative of a need for a suspension redesign, but illustrates the point that while torsional rigidity is a very important aspect of the frame design, there can be a balance where light weight is more beneficial to the overall vehicle dynamics.

The torsion tester for the MY2008 frame utilized the same basic frame to load and restrain the suspension components. Successive 45 lb. weights were added onto the moment arm on the front suspension, and deflection (in the form of degree of twist of the chassis about the center line) was measured. Results from this testing indicate that the MY2008 frame has a rigidity value of between 1800 and 1900 ft. lb/deg., which falls well within the range of the initial simulation estimates.

## 6.0 Future Improvements

### 6.1 *Alternative Materials*

The 4130 chromoly steel spaceframe is easily manufactured and easy to modify during the fabrication phase. However, for teams that are well prepared and experienced in producing structural composites a potential alternative to the spaceframe would be a carbon fiber monocoque chassis. The advantages to this design are the significantly increased strength to weight ratio that composites possess over the alloy steel. For instance, Hexcel ASF4 Carbon Fiber (12,000 Filaments) has an ultimate tensile strength of 4150 MPa and a Modulus of Elasticity of 231 GPa, with a density of only .0643 lb/in<sup>3</sup>. Properly utilized, this material would provide a much stiffer and lighter frame than a steel tubular structure could achieve.

There are several complications in this that present challenges to a team looking to transition to this material. The first is the ability to produce a quality structural composite on a large scale. The amount of detail and attention that needs to be devoted to this project rival the similar amount of resources that need to be allocated to fully machining and welding a spaceframe. Secondly, there are also serious issues in working out hard mounting points in the carbon fiber tub that also conform to the structural requirements in the rules. There are many cases of fatigue-related failures at joints and delaminate, which would be nearly impossible to repair on the spot. Thirdly, there would have to be a significant investment in time and resources to learning how to do a proper carbon fiber analysis, since there are so many variations in the type of weave, epoxy choices, curing conditions, vacuum quality, etc.

In the end, a carbon fiber monocoque is an interesting challenge, but would require a significant shift of resources and expertise to perform correctly. Many of the top teams still run optimized spaceframe

structures that perform as well, if not better, than some of the carbon fiber tubs. For a team with a large amount of resources at its disposal, this may be a feasible alternative in the future.

Other alternatives include the integration of various other materials such as aluminum or titanium as replacements for steel in critical areas because of a desire to lighten and strengthen the chassis.

However, there are also tradeoffs here because of the inability to weld directly to the existing frame, and because of the necessity for a significant amount of additional analysis to justify the design changes.

## 7.0 Conclusion

The MY2008 frame was a significant evolution on past iterations in a number of areas:

- 1) Full retooling of the CAD model to allow for parameterization of critical dimensions and the development of multiple iterations before manufacturing.
- 2) Full FEA analysis and theoretical torsion testing.
- 3) Incorporation of state-of-the-art laser cutting to decrease manufacturing time from several months to less than 2 weeks total.
- 4) Reliable, strong frame manufacturing for component mounting.
- 5) High quality powder coating for professional fit and finish

The entire vehicle hinges on the development of a strong and reliable frame. Because it is a significant time sink of engineering and man hours, it is important to continue to improve the entire production process with the primary goals of weight savings, increased torsional rigidity, shorter manufacturing time, and more analysis and verification. Although the frame is one of the most important components on the vehicle, it is vital to balance its priority in the scheduling and manufacturing portion of the entire vehicle build. Frontloading the production of the frame is a major consideration since it is a major bottleneck to the development process. In fact, the frame and suspension engineers should work closely together during the summer to finalize their designs, even before the academic year begins. As I have learned, it is easy to save days at the beginning of the build, and impossible to save hours near the competition. Many of the failures during competition occurred because of a lack of proper time to finish building and testing the vehicle – any improvements overall in the production of the frame can significantly save time during the overall production.

The Formula SAE frame is one of the most satisfying components on the racecar to develop. Not only is it critical to the look, quality, and performance of the overall vehicle, it is one of the components that is easy to develop and see turned into a reality. At one level, it is a relatively simple system to design and model adequately. However, to develop the winning racecar requires creativity and constant evolution. Frame design is a complicated task, combining both science and art, and a successful designer must be willing to explore both avenues to discover the best design.

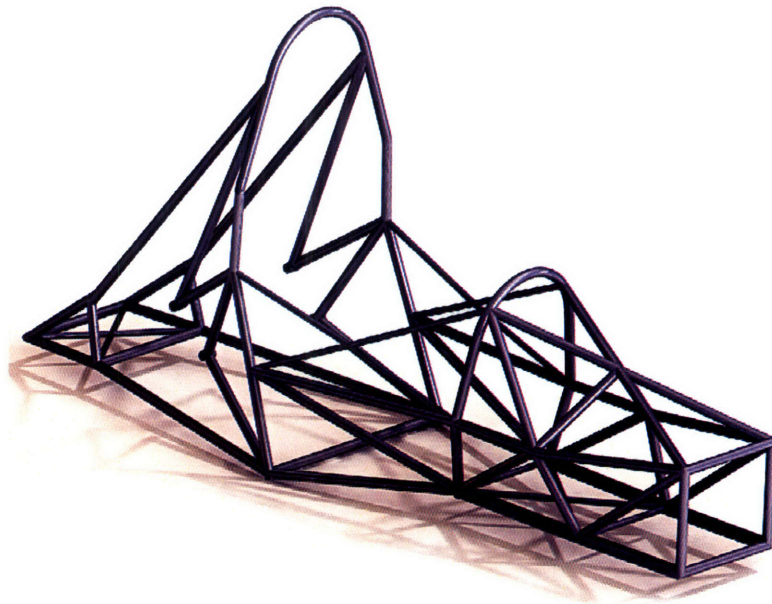


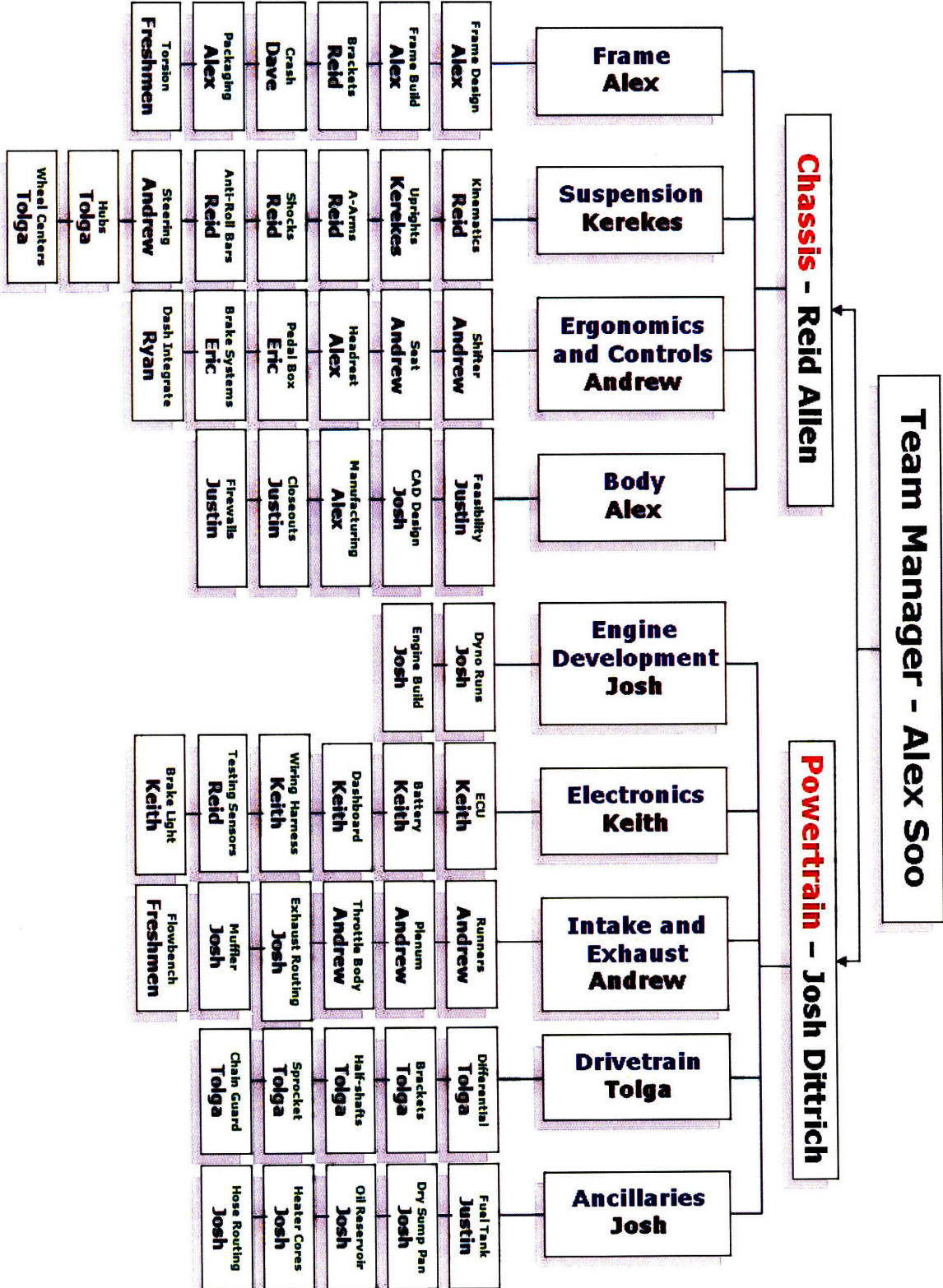
Figure 19: Rendered CAD model of the MY2008 Frame.



Figure 20: Finished vehicle ready for shakedown.

## 8.0 Appendices

### 8.1 Team Organization and Component Chart



## 8.2 Impact Attenuator Documentation



### Massachusetts Institute of Technology Formula SAE® VIR #11      Formula SAE® #25 2008 Impact Attenuator Documentation

**Purpose:** To submit calculations to show that the Impact Attenuator, when mounted on the front of a vehicle with a total mass of 300 kg and run into a solid, non-yielding impact barrier with a velocity of impact of 7 m/s would give an average deceleration of the vehicle not to exceed 20 g.

**Step 1:** Determine crushing strength  $\sigma_c$  for the material selected.

For the 2008 vehicle, we chose Hexcel 5056 Al honeycomb, which has a reported compressive yield strength of 1.01 MPa. In order to verify this, we performed a hemispherical punch indentation test. The results are in Figure 1.

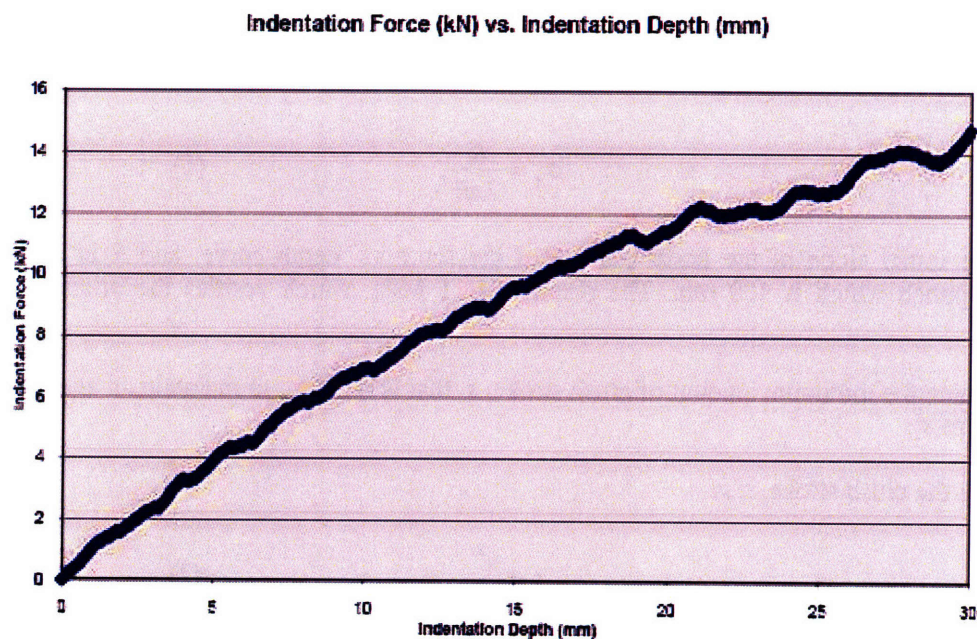


Figure 1: Indentation Force vs. Indentation Depth for 5056 Al honeycomb

In order to obtain  $\sigma_h$ , the linear regime of Figure 1 is used. A linear regression line is applied to the region to determine the slope,  $k$ , of the region. Figure 2 shows the linear portion of the data with the calculated linear regression line.

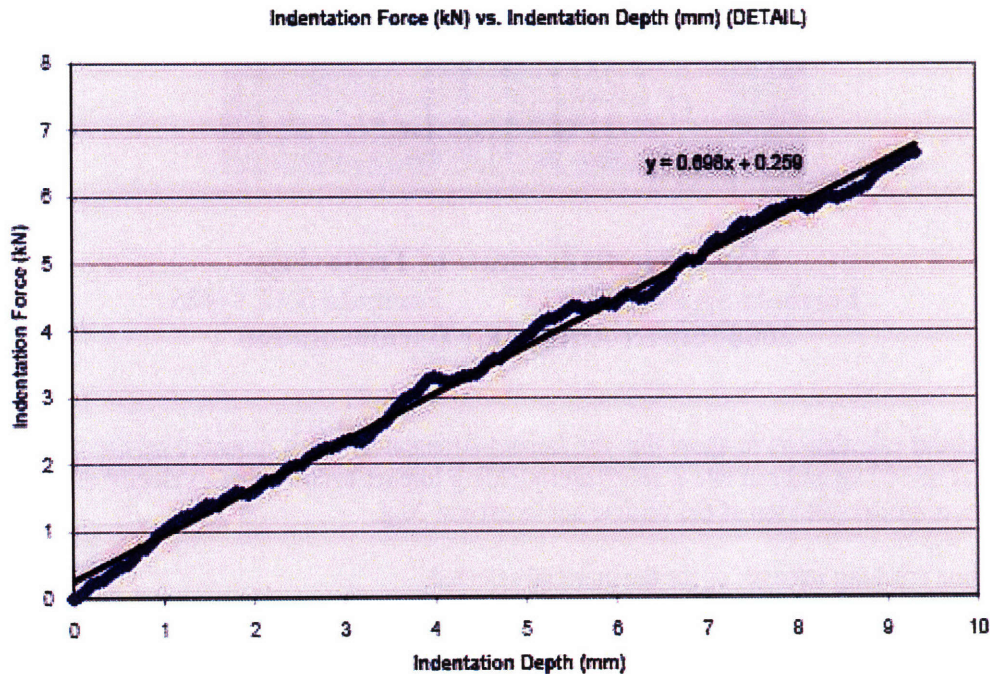


Figure 2: Indentation Force vs. Indentation Depth for the linear region.

From Figure 2,  $\sigma_h$  can be found from,

$$\sigma_h = \frac{K}{2\pi R}, \quad (1)$$

where  $K$  is the initial slope of the linear portion of the force vs. depth curve, and  $R$  is the radius of the hemispherical punch which is 100 mm. The result is 1.11 MPa, which verifies the original claims of the manufacturer.

**Step 2:** Determine the minimum amount of crush stroke,  $s$ , that is required to maintain an average deceleration of 20 g, or 196 m/s<sup>2</sup>.

The formula for the crush stroke,  $s$ , is

$$s = \frac{v^2}{2a}, \quad (2)$$

where  $v$  is the impact velocity of the theoretical car, and  $a$  is the desired deceleration rate.

The crush stroke,  $s$ , is .125 m, which is less than the minimum required depth of the impact attenuator. Therefore, a crash structure built to conform to the rules using this honeycomb will safely accommodate the amount of crush stroke required to maintain a 20 g deceleration.

**Step 3: Determine the maximum amount of impact area,  $A_{impact}$ , necessary to absorb the impact force.**

To determine the maximum amount of impact area,  $A_{impact}$ , the amount of initial external energy is balanced with the amount of energy dissipated by the honeycomb as it is crushed. The formula is

$$m \frac{v^2}{2} = \sigma_h A_{impact} s, \quad (3)$$

where  $m$  is the mass of the car plus driver,  $v$  is the initial velocity at impact,  $\sigma_h$  is the crushing strength of the honeycomb,  $A_{impact}$  is the area of the face perpendicular to impact, and  $s$  is the crush stroke. Rearranged to get  $A_{impact}$ . Equation 3 can be rewritten as

$$A_{impact} = \frac{mv^2}{2s\sigma_h}. \quad (4)$$

Solving Equation 4:

$$A_{impact} = \frac{(300\text{kg} * 49 \frac{\text{m}^2}{\text{s}^2})}{2 * .15\text{m} * 1.11\text{MPa}}$$

$$A_{impact} = .0441 \text{ m}^2$$

The maximum amount of impact area is .0441 m<sup>2</sup> for a crush stroke of .15m, which means that a square impact attenuator must have sides of .21m each.

**Step 4: Verify the equivalency of our impact attenuator geometry.**

The crash structure design is not cubic, however, and in order to fit under the nose cone the structure is tapered near the front end of the car. The base of the structure is widest at the bulkhead with dimensions of 9 x 7.65 in. This maintains the maximum impact area of .0441 m<sup>2</sup>. The front tapers to a 7.5 x 6.5 in. rectangle (.0315m<sup>2</sup>), which is a distance of 8 inches in front of the bulkhead plane. At a distance of 5.9in forward of the bulkhead the cross section is 8.3in wide by 6.8in high, which satisfies the minimum dimensions for the attenuator for a minimum attenuator thickness of 5.9in. In order to verify the equivalency of this sizing, the following equation is used:

$$m \frac{v^2}{2} = \sigma_h s \left( \frac{A_{big} + A_{small}}{2} \right) \quad (5)$$

Solving for  $s$ , it is determined that the new necessary crush stroke is 7.5 inches. Therefore, the dimensions of our crash structure fulfill both the minimum dimensional requirements and also the energy absorption requirements specified by the rules.

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## 10.0 Suppliers

Aircraft Spruce & Specialty Co.  
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