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Formula Electric SAE Frame

David Streen
dcs81@zips.uakron.edu

David Kinion
dsk38@zips.ukron.edu

Dylan Ramey
dar100@zips.uakron.edu

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Advisor:

Dr. Daniel Deckler

Authors:

David Streen
David Kinion
Dylan Ramey

Abstract

The purpose of this project is to design, manufacture, and analyze a steel tube space frame for the Zips Racing Electric team to compete in the FSAE Electric Competition. This report will also serve as a guideline for future Zips Racing Electric team members. This report will include the design of the frame for ZR20e, the welding fixtures needed for its fabrication and a torsion rig to analyze its torsional stiffness. The main purpose for this project is to manufacture a lightweight frame to hold all the components needed by the individual subsystems. Moreover, the frame will be optimized for torsional stiffness, serviceability and weight. Lastly, the frame must meet all FSAE rules and regulations to be eligible for the FSAE Electric competition.

This report includes a detailed description of the design process for an FSAE frame which can be used as a reference for future Zips Racing Electric team members and other FSAE teams.

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1 Introduction

The Formula Electric SAE competition is an engineering design competition in which collegiate teams from across the globe design and build an electric powered race car. The competition evaluates each vehicle on the basis of its engineering design and manufacturing cost in addition to its performance on a racetrack. The vehicle is entirely designed and fabricated by students, which requires cooperation between a team of student engineers. In addition, the vehicle must pass a rigorous technical inspection to ensure it meets the safety guidelines set by FSAE competition rules.

This project involved the design, fabrication, and analysis of the steel tube frame of the Zips Racing Electric's new car, ZR20e, to compete in the FSAE Electric Competition. It also involved the 3D modeling of the structure in addition to an analysis of its torsional stiffness using FEA. Special consideration was given to the rear of the frame and the tubes that support the HV Battery and powertrain components in the FEA.

The vehicle frame is one of the most important systems of a race car. The frame provides the foundation for the rest of the car and its components. The primary goals for designing a frame is to create a structure that is lightweight while maximizing its torsional stiffness. The challenge is to accomplish that goal and still be able to package all the required subsystems in a rules-compliant manner. Decreasing the weight and increasing the torsional stiffness improves speed, handling, and allows for greater success at competition. Optimizing the weight and torsional stiffness can prove difficult because decreasing weight generally decreases the torsional stiffness. Therefore, a clever design with a compromise of weight versus torsional stiffness must be made. The frame also serves as the main safety system to protect the driver in the event of a crash. These are just some of the many factors that were considered when designing the frame for the Zips Racing Electric Team.

The design of the frame began by addressing the overall goals of the Zips Electric Team. To improve upon last year's design, the team decided to focus on improving four areas: vehicle weight, reliability, manufacturability, and serviceability. Specifically, for the frame we strove to reduce weight, maximize torsional stiffness, reduce the number of tubes sizes, and improve driver ergonomics.

2 Design Constraints

Before the frame design can begin it is important to understand the constraints that are in place. The main job of the frame is to house and mount all the subsystem components in the most efficient manner while also meeting the team's overall goals for the entire car. However, the frame must also be safe for a driver to operate and meet all other regulations given by the FSAE rule book. As such the design of the frame must begin with the understanding of all the rules put out by FSAE

2.1 FSAE Rules: General Structure

The design of the frame for Zips Racing Electric's new car, ZR20e, is constrained by the rule set developed by FSAE for the 2020 season. The basis of these rules revolves mostly around safety of the driver and of any bystanders. The rules include requirements that the vehicle must protect the driver in the case of a front impact, side impact, rear impact, and a rollover. In addition, the frame must protect the high voltage components that make up the tractive system from any damage. The tractive system includes the HV motor, the AC/DC inverter, the accumulator or battery pack, and all HV cables connecting components. For clarity and understanding, this section will be divided into the basic areas of the frame.

Front Bulkhead

The front bulkhead is the forward most structure of the frame and is the mounting point for the front crash structure or front impact attenuator. Its main purpose is to protect the driver's feet. The only requirement is rule F.6.1: The front bulkhead must be constructed of closed section tubing of the minimum size per F.3.2.1.a. There are also many considerations in its design including front suspension geometry and a cross sectional area template that will be discussed later.

Front Roll Hoop

The front roll hoop is one portion of the protection system in case of a rollover. It also serves as the main mount for the steering wheel. It has a few rules that need met to ensure safety of the driver.

F.5.6.3: The Front Hoop must extend from the lowest Frame Member on one side of the frame, up, over and down to the lowest Frame Member on the other side of the Frame.

F.5.6.4: The top-most surface of the Front Hoop must be no lower than the top of the steering wheel in any angular position.

F.5.6.5: The Front Hoop must be no more than 250 mm forward of the steering wheel.

F.5.6.6: In side view, the Front Hoop or any part of it must be inclined no more than 20° from the vertical.

While most of these rules are straight forward and easy to follow. It is important to pay attention to steering wheel diameter and location to ensure F.5.6.4&5 are followed as the steering wheel design is developed and finalized. Generally, the angle of the roll hoop is dictated by the front suspension points and it not usually an issue to limit the angle to 20°. In addition, the cross-sectional template rules will need to be considered which will be discussed later.

Front Hoop Bracing

The front hoop braces have the main function of transferring the force from the front bulkhead and resisting the bending of the front hoop in the event of a roll over.

F.6.3.2 The Front Hoop must be supported by two Braces extending in the forward direction, one on each of the left and right sides of the Front Hoop.

F.6.3.3 The Front Hoop Braces must be constructed such that they protect the driver's legs and should extend to the structure in front of the driver's feet.

F.6.3.4 The Front Hoop Braces must be attached as near as possible to the top of the Front Hoop but not more than 50 mm below the top-most surface of the Front Hoop.

F.6.3.5 If the Front Hoop leans rearwards by more than 10° from the vertical, it must be supported by additional Front Hoop Braces to the rear.

F.6.3.6 The Front Hoop Braces must be straight, without any bends

The rules above state that two braces must extend from the front hoop to the front bulkhead. These tubes must attach directly to the top of the bulkhead and within 50 mm from the top of the roll hoop. In addition, if the hoop angles rearward then two additional triangulated braces are required rearward. There are a few allowable configurations that will be discussed later that will depend on suspension and steering geometry.

Front Bulkhead Support

The front bulkhead supports' main function is to support the front bulkhead in a front collision and transfer the forces to the rear of the car around the driver

F.6.2.3: The Front Bulkhead must be supported back to the Front Hoop by a minimum of three Frame Members on each side of the vehicle; an upper member; lower member and diagonal brace to provide Triangulation.

a. The upper support member must be attached within 50 mm of the top surface of the Front Bulkhead and attach to the Front Hoop within a zone extending 100 mm above and 50 mm below the Upper Side Impact member.

b. If the upper support member is further than 100 mm above the Upper Side Impact member, then properly Triangulated bracing is required to transfer load to the Main Hoop, either via the Upper Side Impact member, or an additional member transmitting load from the junction of the Upper Support Member with the Front Hoop.

c. The lower support member must be attached to the base of the Front Bulkhead and the base of the Front Hoop.

d. The diagonal brace must properly Triangulate the upper and lower support members

The bulkhead support is required to have a minimum of three members that transmit force back through the frame, an upper, lower and a triangulation member. Usually the floor structure serves as the lower member. However, the upper member is more flexible if it transfers forces back to the main roll hoop in case of a front impact. This structure is heavily influenced by front suspension geometry. The triangulation member is easily placed after the upper member is decided.

2.1.3 Driver Cockpit

The driver cockpit is the area between the front and main roll hoops which holds the driver. The cockpit is surrounded by the side impact structure which encloses the driver and protects him or her in the event of a collision.

Side Impact Structure (SIS)

F.6.4.4 The Upper Side Impact Member must:

a. Connect the Main Hoop and the Front Hoop.

b. Be entirely in a zone between 240 mm and 320 mm above the lowest point of the Lower Side Impact Member, measured from the top surface of the Lower Side Impact Member

F.6.4.5 The Lower Side Impact Structure member must connect the bottom of the Main Hoop and the bottom of the Front Hoop.

F.6.4.6 The Diagonal Side Impact Member must:

a. Connect the Upper Side Impact Member and Lower Side Impact Member forward of the Main Hoop and rearward of the Front Hoop

b. Completely Triangulate the bays created by the Upper and Lower Side Impact Members.

Generally, the cockpit floor is used as the lower member given the required tube size is used. In addition, the upper side impact member generally can meet the upper front bulkhead support member in the required range given the flexibility in positioning. Behind the main hoop is the mounting for the tractive system components such as the accumulator and motor. In addition, this structure would protect these components and the driver from a rear or side impact and a roll over.

Main Hoop

The main hoop is the second part of the rollover protection system for the driver in case of a rollover. It is also part of the accumulator mounting and protection structure which will be discussed later.

F.5.7.1 The Main Hoop must be constructed of a single piece of uncut, continuous, closed section steel tubing

F.5.7.2 The Main Hoop must extend from the lowest Frame Member on one side of the Frame, up, over and down to the lowest Frame Member on other side of the Frame.

F.5.7.3 In the side view of the vehicle,

a. The portion of the Main Hoop that lies above its attachment point to the upper Side Impact Tube must be within 10° of the vertical.

b. Any bends in the Main Hoop above its attachment point to the Major Structure of the Chassis must be braced to a node of the Main Hoop Bracing Support structure.

c. The portion of the Main Hoop that lies below the upper side impact member attachment point may be inclined at any angle to the vertical in the forward direction but, it must be inclined rearward no more than 10° of the vertical.

F.5.7.4 In the front view of the vehicle, the vertical members of the Main Hoop must be at least 380 mm apart (inside dimension) at the location where the Main Hoop is attached to the bottom tubes of the Major Structure of the Chassis.

The rules that govern the main roll hoop are straightforward if it is exactly perpendicular to the ground. When side view bends are introduced, or the hoop is angled forward or rearward the rules become more complex. Generally, multiplane bends are avoided due to the added complexity in which case the roll hoop can be angled a max of 10 deg. In the case of an Electric FSAE car, the main reason to include an angled roll hoop would be to provide packaging flexibility for the accumulator. The considerations for such a situation will be discussed later.

Main Hoop Bracing

Like the front hoop braces, the main hoop braces support the main hoop in the event of a rollover.

F.5.8.1 Main Hoop Braces must be constructed of closed section steel tubing

F.5.8.2 The Main Hoop must be supported by two Braces extending in the forward or rearward direction, one on each of the left and right sides of the Main Hoop.

F.5.8.3 In the side view of the Frame, the Main Hoop and the Main Hoop Braces must not lie on the same side of the vertical line through the top of the Main Hoop.

F.5.8.4 The Main Hoop Braces must be attached within 160 mm below the topmost surface of the Main Hoop.

F.5.8.5 The included angle formed by the Main Hoop and the Main Hoop Braces must be at least 30°.

F.5.8.6 The Main Hoop Braces must be straight, without any bends.

Outside of the general requirements such as tube size and number of braces, the main concern will be the location in relation to the top of the hoop and the angle from the hoop. With that in mind, the requirements that the braces be straight, angled at a minimum degree, and located close to the top of the hoop within an allowance are more easily understood. In general, these rules are independent of other design considerations, but will need to be checked as the frame design evolves.

Main Hoop Bracing Supports

F.6.6.2 The lower end of the Main Hoop Braces must be supported back to the Main Hoop by a minimum of two Frame Members on each side of the vehicle: an upper member and a lower member in a properly Triangulated configuration.

a. The upper support member must attach to the node where the upper Side Impact Member attaches to the Main Hoop.

b. The lower support member must attach to the node where the lower Side Impact Member attaches to the Main Hoop.

c. Each of the above members may be multiple or bent tubes

The basis of this rule is requiring that the hoop braces be supported back to the main hoop by at least 2 triangulated tubes meeting at the SIS. These tubes are generally easy to place after consideration of rear suspension mounting points and tractive system protection. An important note is that the supports can be multiple tubes which offers a lot of flexibility.

Tractive System Protection

The rules state that all the tractive system components must be protected by a minimum tube structure. These tubes have the added requirement of supporting the rear suspension mounts and roll hoop brace supports.

F.11.2: From the side, below 350mm, the tractive HV components must be protected with:

1: An upper tube, generally no above Upper SIS height or below the top of a motor at axle level

2: A lower Tube

3: A diagonal tube or tubes completely triangulating the upper and lower tubes

This structure is basically a repeat of the existing SIS structure to protect the tractive system.

2.2 FSAE Rules: Driver Safety

In addition to rules directly stating the size of tubes and their placement, there are also a few indirect rules that can dictate tube locations. These rules are defined using templates that correspond to minimum space requirements for drivers of different sizes and the space required for the safe egress in case of emergency. There are three templates that must fit within the frame with specific criteria: the driver template (Percy), the cockpit opening, and the internal cross section.

Driver Template

F.5.5.4 A two-dimensional template used to represent the 95th percentile male is made to the following dimensions (see figure below):

- A circle of diameter 200 mm will represent the hips and buttocks.
- A circle of diameter 200 mm will represent the shoulder/cervical region.
- A circle of diameter 300 mm will represent the head (with helmet).
- A straight line measuring 490 mm will connect the centers of the two 200 mm circles.
- A straight line measuring 280 mm will connect the centers of the upper 200 mm circle and the 300 mm head circle.

F.5.5.5 The Driver Template will be positioned as follows:

- The seat will be adjusted to the rearmost position
- The pedals will be placed in the most forward position
- The bottom 200 mm circle will be placed on the seat bottom such that the distance between the center of this circle and the rearmost face of the pedals is no less than 915 mm
- The middle 200 mm circle, representing the shoulders, will be positioned on the seat back
- The upper 300 mm circle will be positioned no more than 25 mm away from the head restraint (where the driver’s helmet would normally be located while driving)

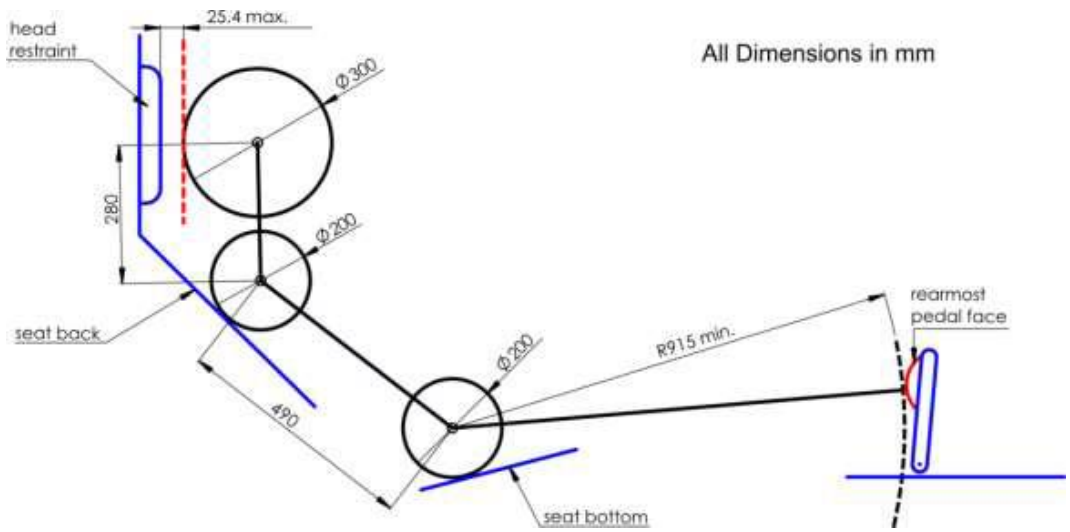


Figure 2.2.1: Driver Template Requirements

In simple terms, the Driver Template represents any driver that may operate the vehicle and defines requirements for its positioning to ensure comfort and safety. These requirements will influence many decisions in the design of the frame including the distance between the bulkhead and front hoop, height of the roll hoops, and location of the throttle and brake pedals.

Cockpit Opening

The cockpit opening represents the minimum amount of space required to allow the driver to safely enter and exit the cockpit.

T.1.1.1 The template shown below must fit into the cockpit opening.

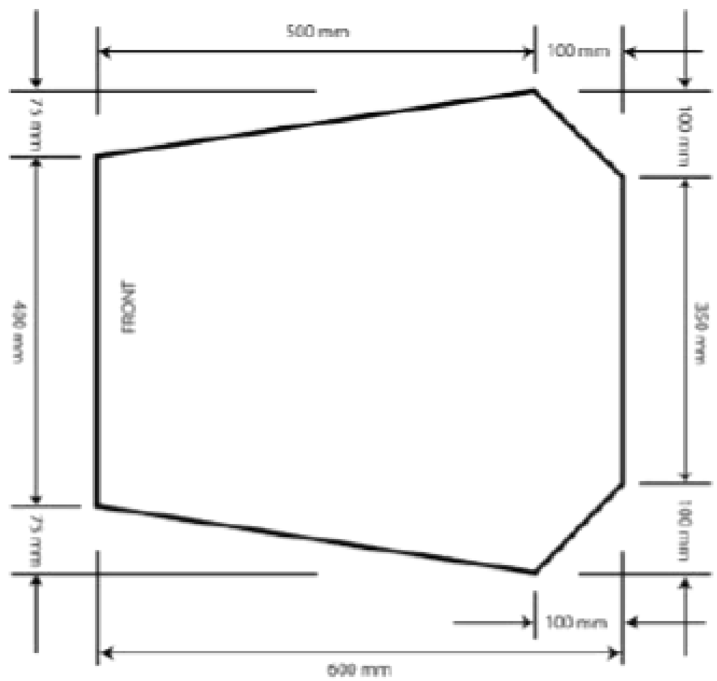


Figure 2.2.2: Cockpit Opening Template Dimensions

T.1.1.2 The template will be held horizontally, parallel to the ground, and inserted vertically from a height above any Primary Structure or bodywork that is between the Front Hoop and the Main Hoop until it has passed below the top bar of the Side Impact Structure

T.1.1.3 Fore and aft translation of the template is permitted during insertion.

T.1.1.4 During this test:

a. The steering wheel, steering column, seat and all padding may be removed.

b. The shifter or shift mechanism may not be removed unless it is integral with the steering wheel and is removed with the steering wheel.

c. The firewall must not be moved or removed.

d. Cables, wires, hoses, tubes, etc. must not impede the template

In simple terms this template must fit from the top of the cockpit to the top of the seat. This ensures that the driver can eject out his or her seat and egress from frame without issue. The driver is required to be able to exit vehicle within 5 seconds while in normal driving position.

Internal Cross Section

The internal cross section template represents the driver's feet and is the minimum required area to allow the driver to safely exit frame.

T.1.2.1 A free internal cross section to allow the template shown below to pass through must be maintained through the cockpit.

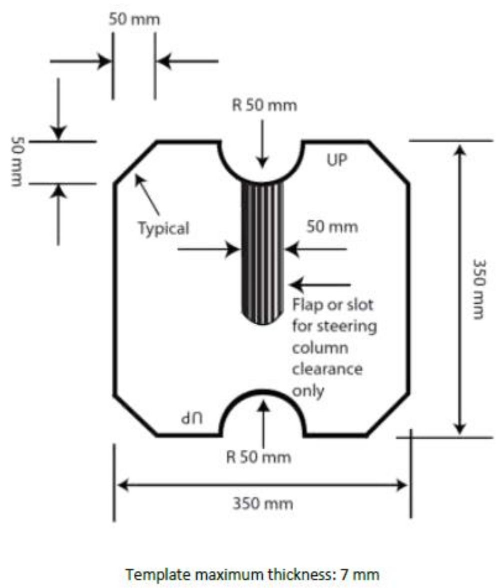


Figure 2.2.3: Internal Cross Section Template Dimensions

T.1.2.2 Conduct of the test:

a. The template will be held vertically and inserted into the cockpit opening rearward of the rearmost portion of the steering column.

b. The template will then be passed horizontally through the cockpit to a point 100 mm rearwards of the face of the rearmost pedal when in the inoperative position

T.1.2.3 During this test:

a. If the pedals are adjustable, they must be in their most forward position.

b. The steering wheel may be removed

c. Padding may be removed if it can be easily removed without the use of tools with the driver in the seat

d. The seat and any seat insert(s) that may be used must remain in the cockpit

e. Cables, wires, hoses, tubes, etc. must not impede the template

The possibilities of front suspension points are directly affected by this template. It is important to ensure that chosen suspension points and steering rack placement allow this template to extend up to the pedal faces without interference. In addition, other rules such as T.1.3, T.1.4, and T.1.5 require that driver, all controls, and the seat are contained within the frame tubes. These rules are generally not an issue to abide by.

Driver Harness

The vehicle will be equipped with a 6-point driver harness which consists of two lap belts, two shoulder belts, and two anti-submarine belts. Each of which must be securely attached to the frame. The lap and anti-sub belts must mount to a bracket, but the shoulder belts are able to be wrapped around a frame member.

T.2.4.3: Each tab or bracket to which any harness is attached must:

a. Have a minimum cross-sectional area of 60 mm^2 of steel to be sheared or failed in tension at any point of the tab

b. Be 1.6 mm minimum thickness

c. Be aligned such that it is not put in bending when the attached part of the harness is put under load.

d. Where lap belts and anti-submarine belts use the same attachment point, there must be a minimum cross-sectional area of 90 mm^2 of steel to be sheared or failed in tension at any point of the tab.

e. Not cause abrasion to the belt webbing

Shoulder Harness Mounting

F.6.5.1 The Shoulder Harness Mounting Bar must:

a. Be a single piece of uncut, continuous, closed section steel tubing

b. Attach to the Main Hoop on both sides of the chassis

F.6.5.2 Bent Shoulder Harness Mounting Bars must have bracing members attached at the bend(s) and to the Main Hoop. The included angle in side view between the Shoulder Harness Bar and the braces must be no less than 30°.

The shoulder harness bar has straightforward requirements with options for a straight bar or a bent tube between the main roll hoop. The positioning of this tube is required to allow the shoulder harness to meet rule T.2.6.2. From the driver's shoulders rearwards to the mounting point or structural guide, the shoulder harness must be between 10° above the horizontal and 20° below the horizontal.

2.3 Subsystem Integration

While the rules govern some tube sizes and relative placements, the design of the frame has a lot of flexibility. As mentioned before, much of the design revolves around the subsystems and their component mounting needs. The most important of these is the front and rear suspension mounts since they will dictate the cars handling, followed by the placement of the battery pack which is generally the largest mass in the car, followed again by the driver, another large mass buts who has to race the car and ultimately score points.

By analyzing the last years frame, it was determined that the main contributor to the faults of last year’s frame design was the location and size of the accumulator. Last year, the accumulator was positioned in the front of the main hoop under the driver seat. This forced the frame to have a large side impact structure in order to accommodate its width. Reducing this structure would remove a substantial amount of weight from the frame. This would also allow the car to have a narrower track width which will improve its handling in corners. By working with accumulator subsystem team, a more compact structure was designed that will allow it to be placed behind the main roll hoop. The placement of the accumulator behind the main hoop has many advantages. Driver ergonomics are improved by making the driver seat more upright. The mid-section of the frame is simpler which will reduce manufacturing time due to the few number of tubes and tube sizes required. Serviceability is improved because the previous accumulator could only be serviced through the cockpit while a rear mount allows the accumulator to drop straight down out of the frame with ease.

The suspension mounting points dictate the placement of many of the tubes and nodes either directly or indirectly. It was decided early on that the front suspension points would be very similar to the ones used on the 2019 car since it handled very well. However, the rear suspension points would have to be re configurated due to the new accumulator and rear packaging needs. The mounting of the motor, AC/DC inverter, and the differential also must be considered to ensure the powertrain can reach its maximum potential. Balancing the rules and the needs of the car requires compromises to be made for the frame to be optimized to the fullest potential.

3 Detailed Design

The design of the frame was developed using the rules stated above and the initial assumptions and designs given by the individual subsystem teams. The initial design is made in stages, beginning with the creation of a wireframe model and ending with the addition of the tube profiles. As subsystem designs are updated and finalized, changes to the frame design are made. The process shown below shows the final version of the frame, however certain dimensions and node locations evolved as necessary to meet the needs of the subsystems throughout the design process although they are not explicitly mentioned.

3.1 Model Setup and Configuration

Before the modeling process can start, a coordinate system and planes need to be created to create a reference point between the different software packages we use to aid in manufacturing. SolidWorks 2019-2020 was used exclusively for the design of this frame. From a new part file, the front, top, and right planes were renamed to ground, mid, and suspension reference, respectively. The ground plane represents where the wheels will be at ride height. The mid plane represents the mirror plane of the frame lengthwise. The suspension reference plane is used as a reference plane for the input of suspension geometry from the kinematics program that the suspension team uses for their design. With the new plane definitions, the coordinate system is as follows. The X axis will be along the length of the frame on the mid plane. The positive Y axis will be the right side of frame from driver perspective and the negative Y axis will be the left side of frame. The positive Z axis will extend upward from the ground plane.

Preliminary Suspension Points

The suspension mounting points define many aspects of the car, especially in the front section. Therefore, it is helpful to get a rough idea of their placement before the frame design begins. Suspension points are imported into the frame model with fixed 3D coordinates directly from a kinematics program. The points shown in this report are the final points used on the frame. Note that the suspension points were revised several times during the design phase although not mentioned explicitly in this report.

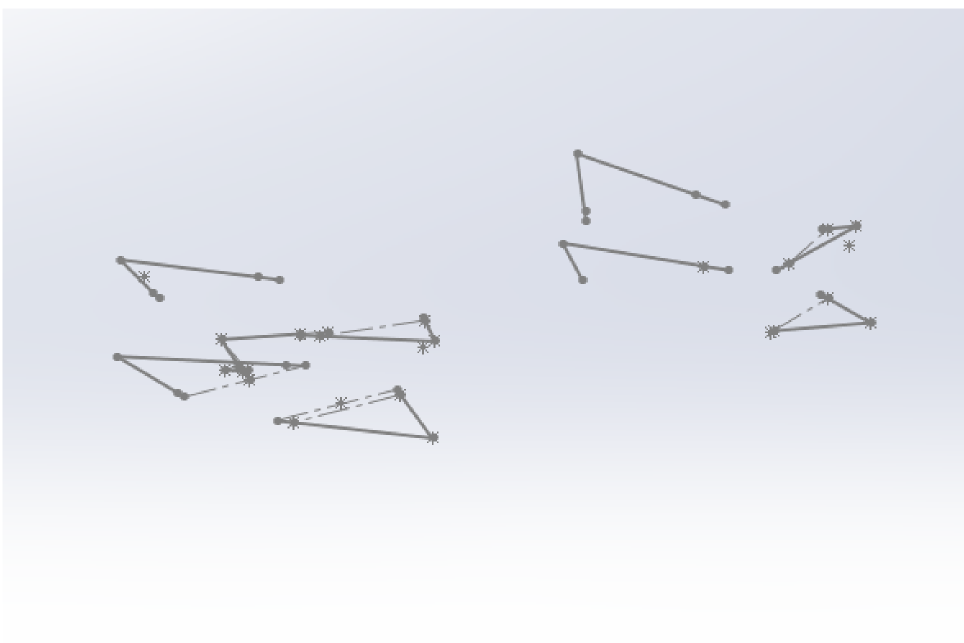


Figure 3.1.1: 3D sketch showing the suspension points of ZR20e

3.2 Wireframe Model

The front hoop will serve as the starting point for the chassis design. It provides a stout structure for the front suspension points and allows a direct comparison between previous car designs. Since the hoop needs to extend from one side of frame to other per rule F.5.6.3, multiple bends will be needed. It is good practice that each bend in the roll hoop be a node in the frame to ensure proper force transfer and prevent tubes from experiencing bending loads. The upper and lower aft points will define the lower two nodes of the hoop. In addition, the lower front suspension points will define the width of the front floor. The location of the front bulkhead, primarily on the driver seating position, is placed 825 mm from the front hoop. This location was revised as the driver's seating position was developed.

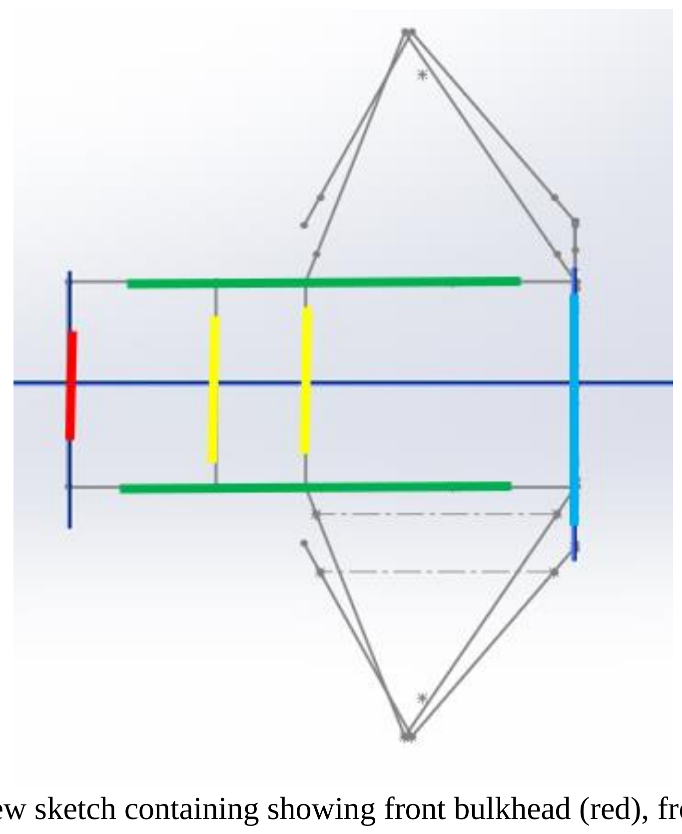


Figure 3.2.1: Top view sketch containing showing front bulkhead (red), front hoop (blue), front floor (green), cross members (yellow)

Front Bulkhead Supports

The sides of the front section are defined around the front upper fore suspension point in accordance with the front bulkhead support rules. The upper member defined in Rule F.6.2.3a will start at the bulkhead, extend through the upper fore suspension point, and end at the upper aft suspension point, creating a total of two members. The lower frame rail making up the front floor will be considered the lower front bulkhead support tube regulated by F.6.2.3c. To provide the necessary triangulation, three additional members are added to the model. In addition, since the upper front bulkhead support member consists of 2 members, Rule F.5.2.3 applies.

F.5.2.3 If a bent tube (or member consisting of multiple tubes that are not in a line) is used anywhere in the Primary Structure other than the Roll Hoops, an additional tube must be attached to support it.

a. The attachment point must be the position along the tube where it deviates farthest from a straight line connecting both ends.

b. The support tube must have the same diameter and thickness as the bent tube, terminate at a node of the chassis, and be angled no more than 30° from the plane of the bent tube.

To meet Rule F.5.2.3, another member is added from the front roll hoop to the upper fore suspension point making a total of 6 tubes meeting at that node.

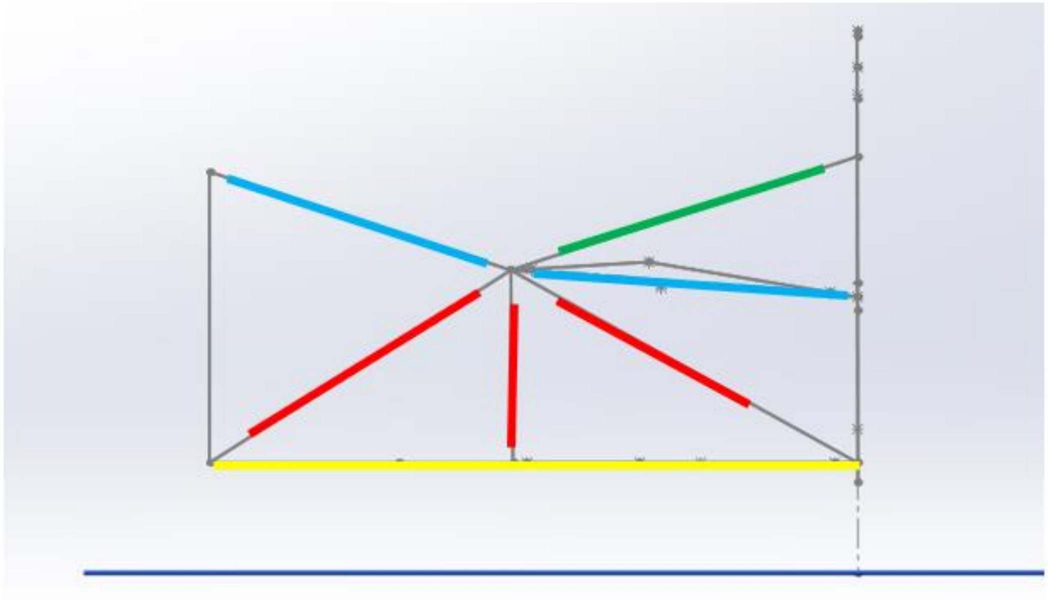


Figure 3.2.2: Side view of frame showing front bulkhead support upper members (blue), lower member (yellow), triangulation members (red), and F.5.2.3 member (green)

Front Hoop Braces

The front hoop braces will complete the front structure directly following requirements from rule F.6.3. The braces are designed to mount to the front roll hoop at distance of 45 mm from the top in order to meet the limit of 50 mm and allow for any manufacturing error. In addition, the braces will end at the top of the front bulkhead to protect the driver's feet and provide as much room as possible for the cross-section template. From these nodes, there are two possibilities for tube placement: two independent straight members or an X brace configuration. The X brace configuration allows for an increase in torsional stiffness and provides a strong attachment point for a steering column support. While the Structural Equivalency Spreadsheet (SES) used in conjunction with FSAE Rules discourages an X brace configuration, it is allowed and will be used. A bend is incorporated to the top of the front hoop to allow it to have the tallest height with the least amount of material. Rule F.5.2.1 requires that the minimum radius of any bend, measured at the tube centerline (CLR), must be at least three times the tube outside diameter (3 x OD).

Due to geometry and manufacturing constraints that occur with 5 or more bends in a single length of tubing, the front hoop braces would not be able to mount to a node like the other tubes attaching to the hoop. This type of attachment results in the roll hoop tube being subjected to a lateral load which is its weaker direction and therefore discouraged. In order to minimize the effect of this load the front hoop brace is designed to mount at the midpoint of the 2 adjacent nodes.

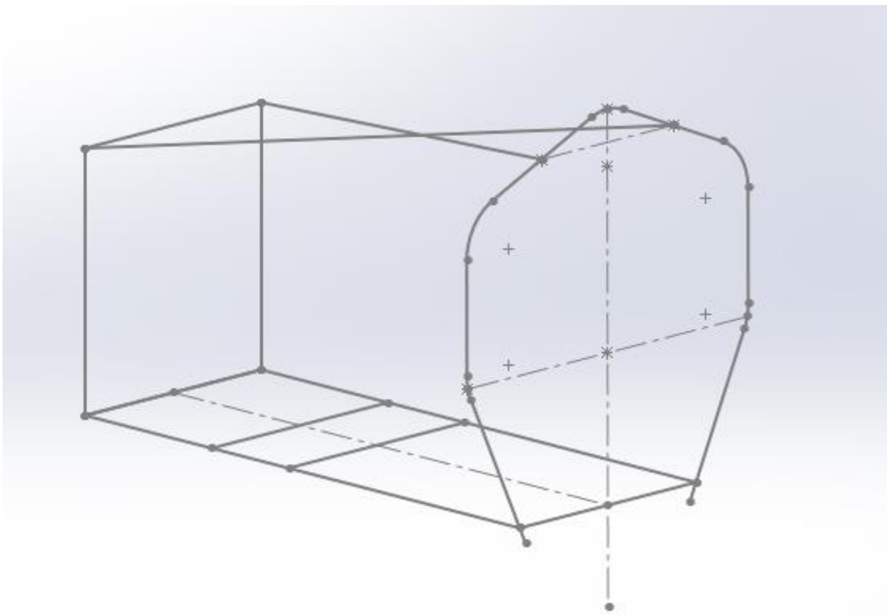


Figure 3.2.3: Isometric view of the front of the frame with the front hoop braces. (Note: front bulkhead support members have been removed for clarity)

Cockpit

With the preliminary design of the front structure completed, the driver cockpit can be developed. The cockpit floor can be defined in relation to the ground plane. In order to keep the center of gravity low, race cars are designed to have very little ground clearance. Considering the

2-inch total suspension travel of the car and the 1-inch OD of the frame tubes, the cockpit floor can be placed 1.875 inches above the ground plane to provide a small but safe amount of clearance. To transition from the front floor to the cockpit floor, an angled section is introduced. The end of the section is defined as 10.50 inches from the front hoop to provide a visual balance between the angle of the transition and the length of the cockpit floor. This location was updated as the driver seat and driving position was developed.

The placement of the main hoop is dependent on the cockpit opening and the accumulator's size and placement. For ZR20e, it was decided that the accumulator will be mounted rearward of the main roll hoop instead of under the driver seat forward of the main hoop as it was in the last car. This allows some of the area under the seat to be used for other components such as the ECU, LV battery, and the fuse panel. Since those components will not be able to utilize all the space under the seat, an angled hoop will be introduced to allow some of that space to be used by other components. To meet rule F.5.7.3, the roll hoop will be angled 8 degrees rearward with the pivot point at the top of the cockpit structure. This allows the area under the seat to be reduced while still allowing the cockpit opening template to fit. Figure 3.2.2 shows the Cockpit floor (green) and its end point 10.5 inch from the front hoop (yellow) and the pivot point in blue

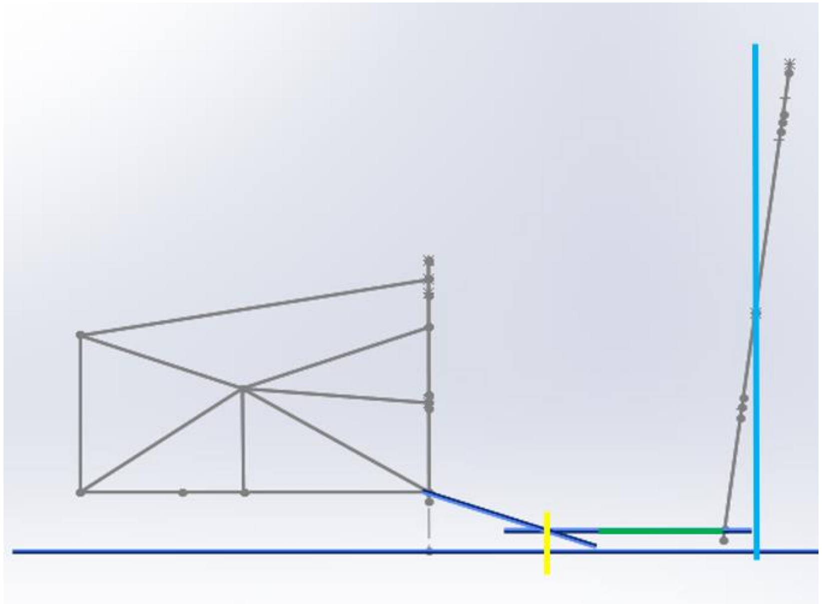


Figure 3.2.3: Side view of cockpit structure showing the angled main hoop and floor structure

In order to fully define the cockpit floor structure and provide optimal force transfer, additional planes are needed. An axis is defined using the bottom of the front hoop and the bottom of the main hoop and then a plane along that axis and perpendicular to the ground was also defined.

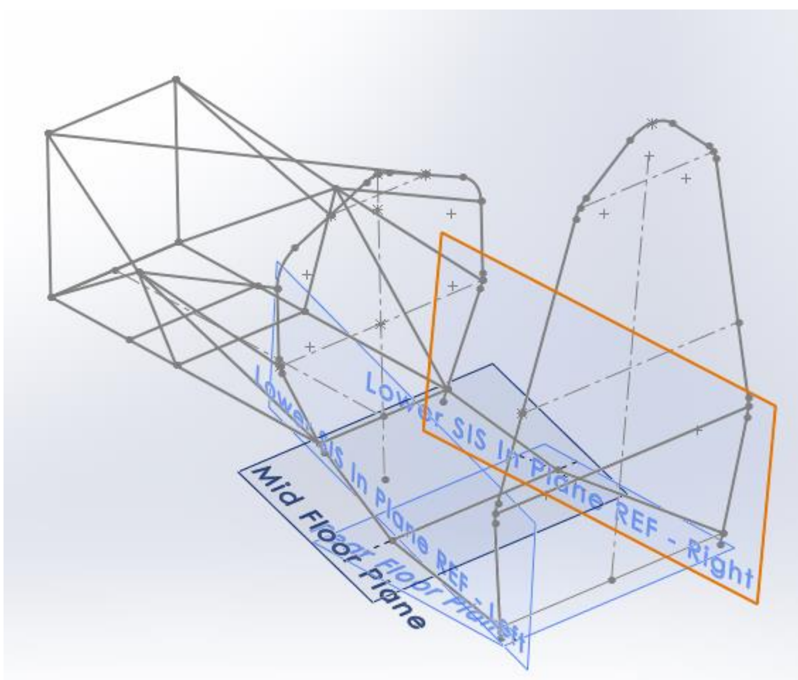


Figure 3.2.4: Isometric view of frame showing the 4 planes used to sketch the cockpit floor

Using the 3 planes the cockpit floor structure sketch is fully defined.

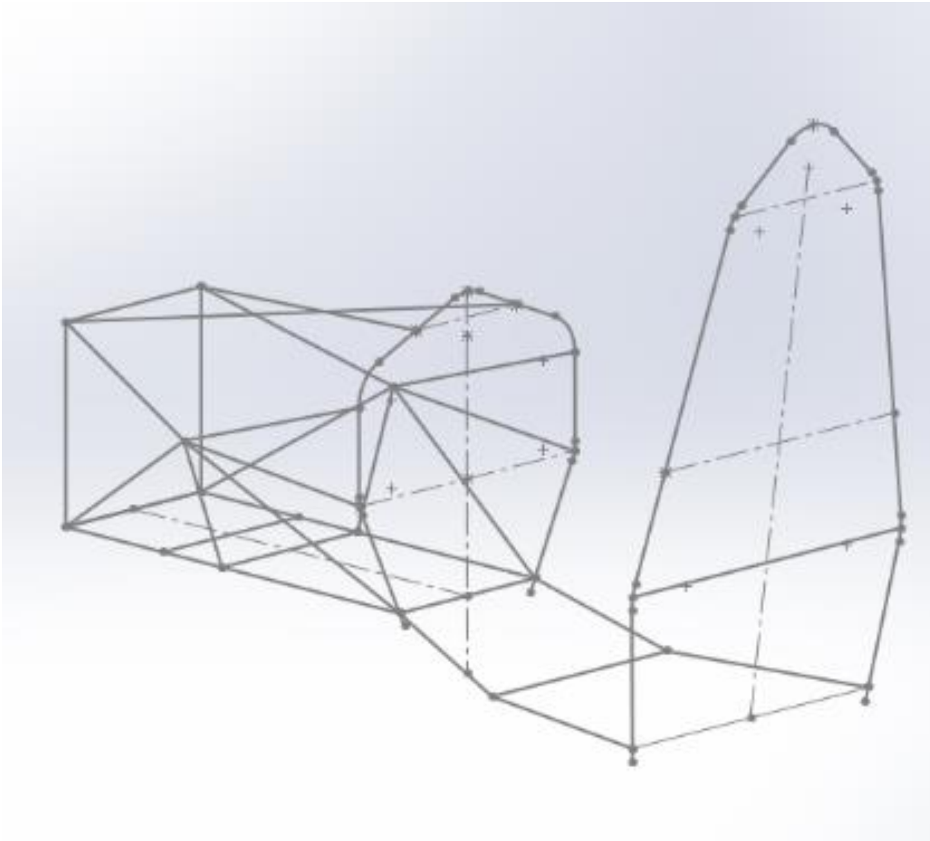


Figure 3.2.5: Isometric view showing fully defined cockpit floor structure

Since the Accumulator sits directly behind the main hoop, the width of the accumulator, which is 22”, will directly define the width at the bottom of the hoop. In addition, the 11-inch height of proposed accumulator along with the front upper aft suspension point defines the upper SIS member. The length of the proposed accumulator, which is 17”, is used to define a plane offset from the bottom of the main hoop which will be used to define the floor the accumulator will sit on. Figure 3.2.6 shows the accumulator length plane (blue) offset form the roll hoop bottom (yellow) and the upper SIS member within the regulations defined in rule F.6.4.4b.

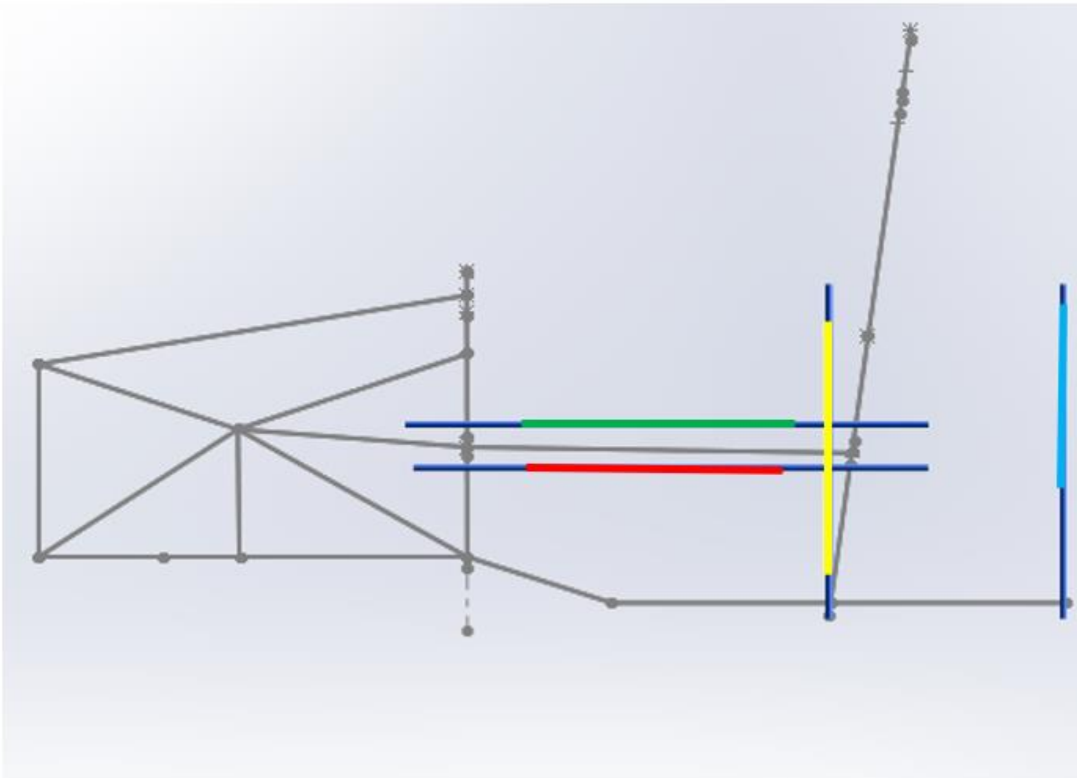


Figure 3.2.6: Side view showing upper SIS member within rules requirements and the accumulator reference planes

Accumulator and Powertrain Box

The rearmost section of the chassis houses many of the powertrain components for the car and will be named the powertrain box. This structure generally is defined using the rear suspension points but due to the constraints on the accumulator, the powertrain box must share a node with the accumulator floor. In addition, Rule F.11.2 requires that the upper protection member for the accumulator must be above the top of the accumulator which the upper fore suspension point does not meet. While not desired, both upper and lower fore suspension points will need to be offset from frame nodes. A reference plane based on the accumulator floor and the upper suspension point is used to define the beginning of the powertrain box as shown in Figure 3.2.7. To meet the requirements of F.11.2, a point was created on the plane 9.75 inches from the accumulator floor, measured normal to the plane. This location meets the requirements of F.11.2 and minimizes the offset distance of the suspension point.

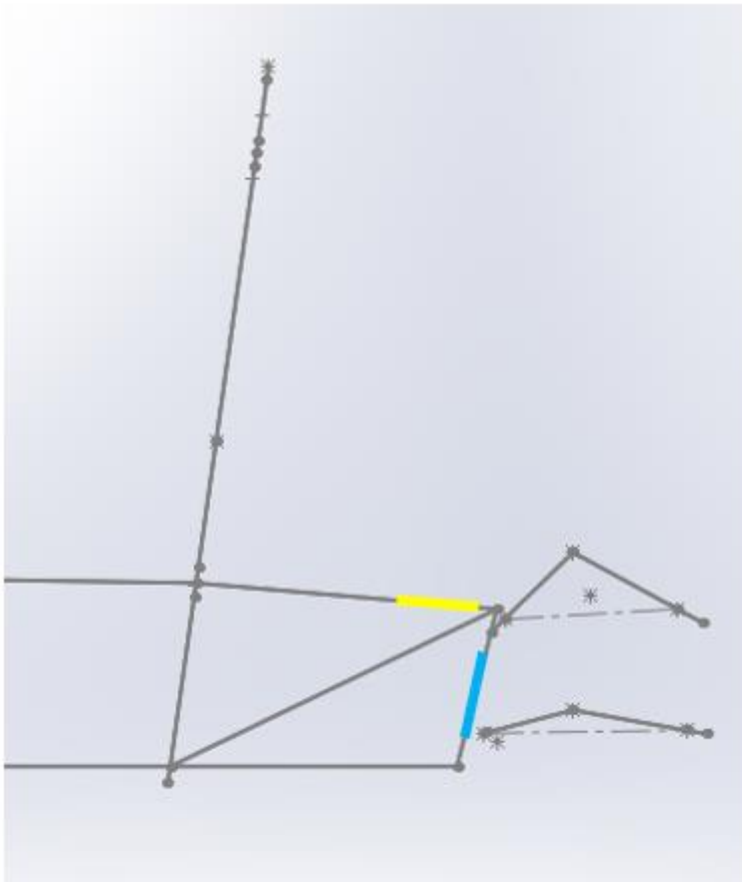


Figure 3.2.7: Side view showing powertrain box development; reference plane location (blue) and the upper protection member located 9.75 inches along the reference plane (yellow)

The aft suspension points will be used to complete the powertrain box and the lower portion of the rear frame. Since the cv axles must exit the frame from the powertrain box, the triangulation will need to be designed so it does not interfere. Since the differential is mounted in the center of the powertrain box, the standard cross beam triangulation would run directly through the axle’s path. To prevent this, a “V” style triangulation was be used to create a space for the axles to exit the frame.

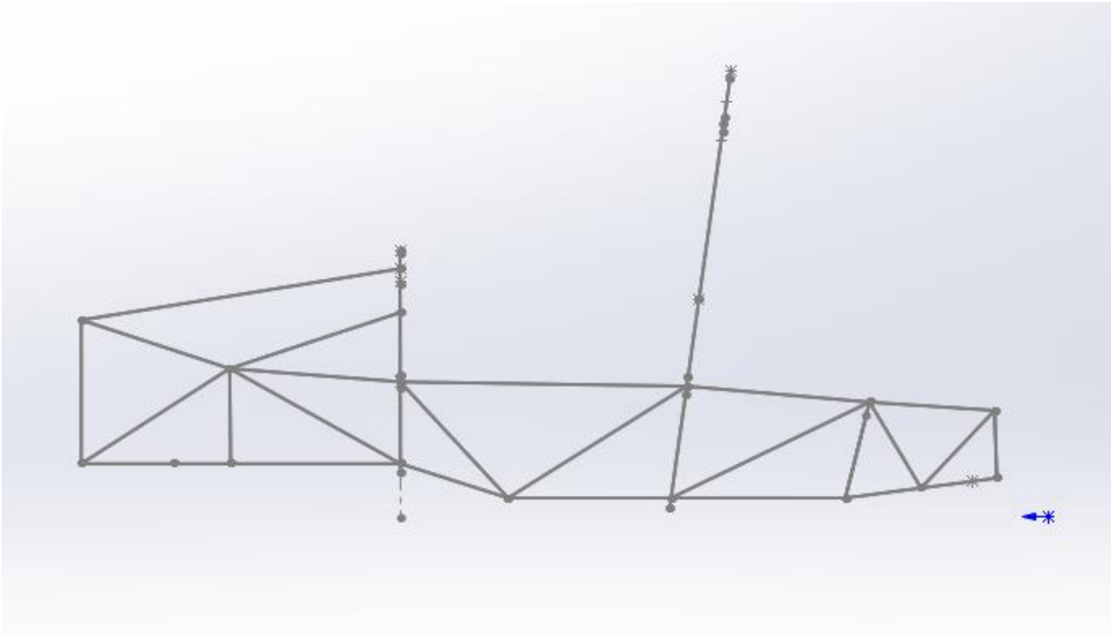


Figure 3.2.8: Side view showing complete powertrain and accumulator box

Main Hoop Braces and Supports

The next section of the frame to be developed is the main hoop braces and any necessary supports. An easy solution is to include a member from the top of the roll hoop to the rear aft point of the rear suspension. However, with the accumulator taking up the space in the lower section, the inverter will need to be mounted directly above it. An additional tubing structure will be added to provide a mounting point for the inverter. Due to the small size of the powertrain box, the motor must be mounted above the differential. Rule F.11 requires that all parts of tractive system must be enclosed in a protective structure or be in the car’s rollover protection envelope, defined by Rule F.1.1.L.

F.1.1.L the Primary Structure plus a plane from the top of the Main Hoop to the top of the Front Hoop, plus a plane from the top of the Main Hoop to the rearmost Triangulated structural tube, or monocoque equivalent.

With the above considerations and rules in mind, the Main Hoop Braces will form a 32-degree angle to the Main Hoop. Two additional tubes will meet at the brace node and attach to the upper SIS node and the rear fore suspension node to meet Rule F.6.6.2. In addition, to ensure the motor is protected, an additional tube will be added at the rear aft suspension node.

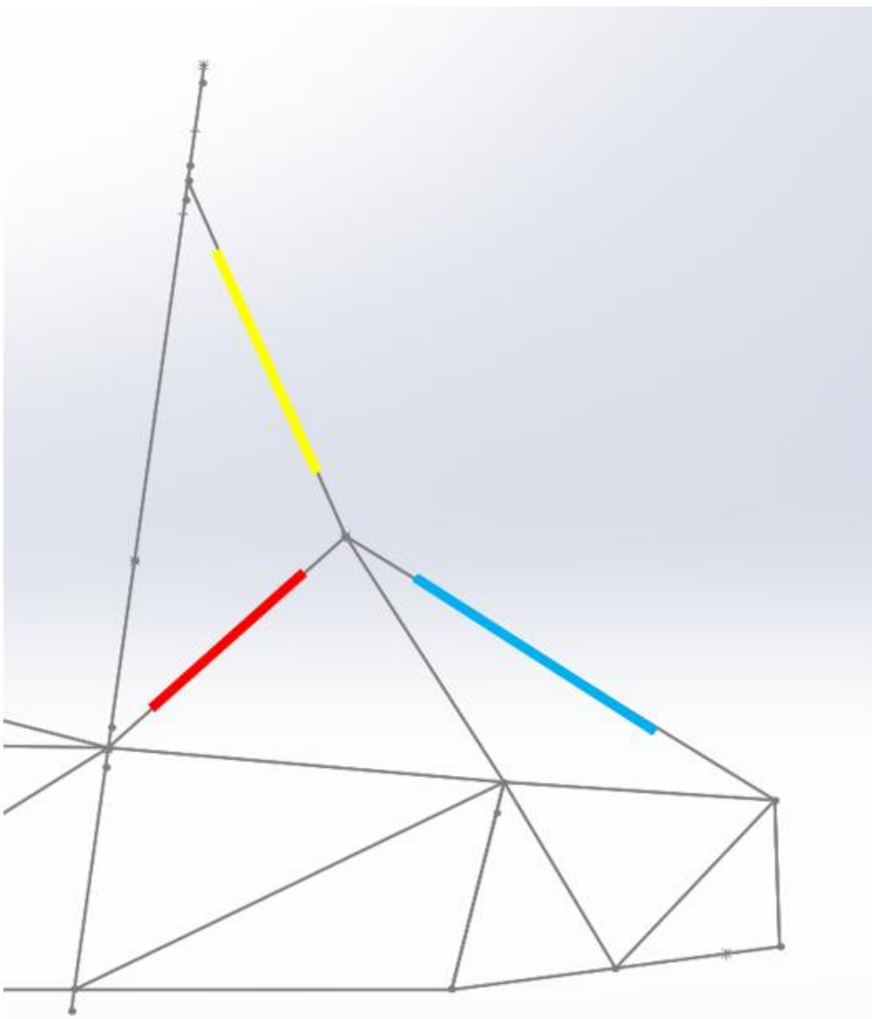


Figure 3.2.9: side view showing Main Hoop Brace (yellow), Rule F.11.L Protection member (blue), and inverter mount tube (red).

Shoulder Harness Bar and Head Restraint

The placement of these frame members tubes is dependent on the driver's placement. A bent harness bar is desirable over a straight bar since it provides more flexibility. A bent bar allows the driver's shoulders to extend behind the main hoop in addition to providing a convenient attachment point for the head restraint structure. To meet the angle requirement of Rule T.2.6.2 and minimize the length of the bend support required by Rule F.6.5.2, the harness bar is angled upward slightly.

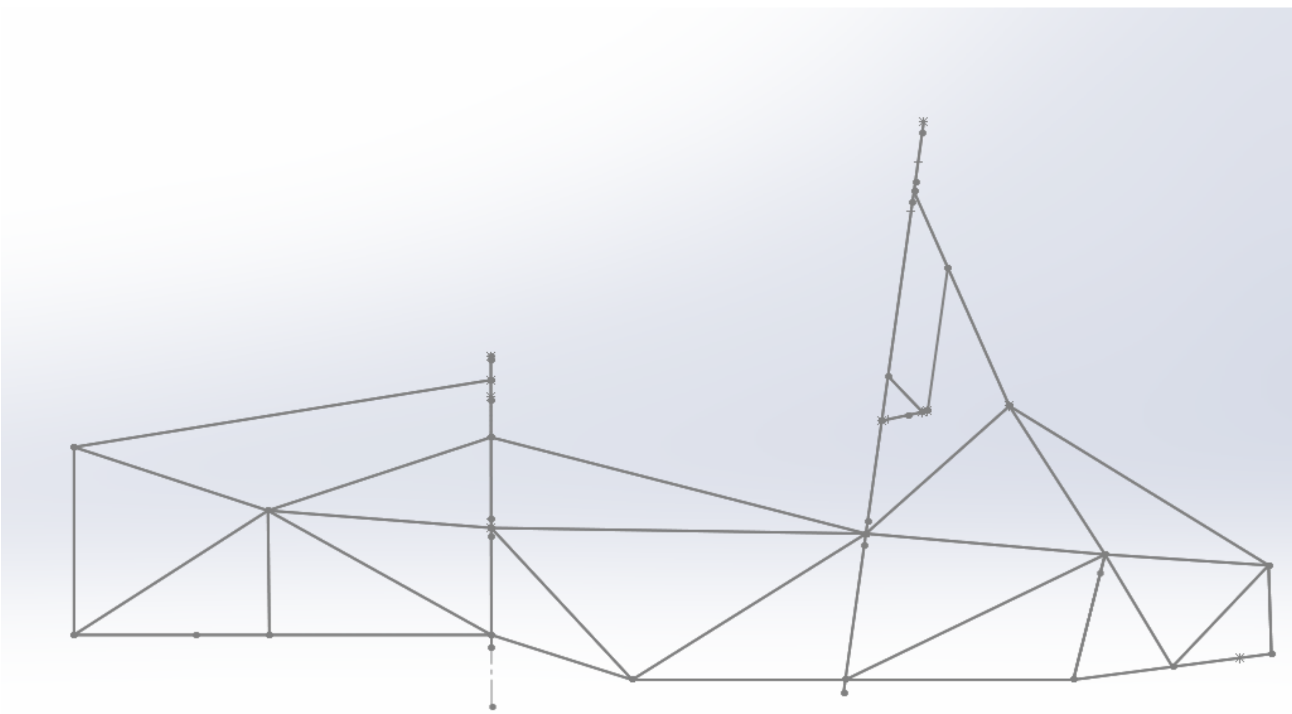


Figure 3.2.10: Side view of the complete wireframe model of frame

3.3 Tubing Model

With the wireframe model complete, the next step is to add in the tubes and the necessary notches and miters. Tubing is added using the minimum requirements stated in Rule F.3.2.1.

	Application	Steel Tube Must Meet Size per F.3.4:
a.	Front Bulkhead	Size B
b.	Front Bulkhead Support	Size C
c.	Front Hoop	Size A
d.	Front Hoop Bracing	Size B
e.	Side Impact Structure	Size B
f.	Bent Upper Side Impact Member	Size D
g.	Main Hoop	Size A
h.	Main Hoop Bracing	Size B
i.	Main Hoop Bracing Supports	Size C
j.	Driver Restraint Harness Attachment	Size B
k.	Shoulder Harness Mounting Bar	Size A
l.	Shoulder Harness Mounting Bar Bracing	Size C
m.	(EV) Accumulator Protection Structure	Size B
n.	Component Protection	Size C
o.	Other Structural Tubing	Size C

Figure 3.3.1: Chart from FSAE Rule Book showing the minimum tube sizes for each section of the frame per Rule F.3.2.1

	Tube	Minimum Area Moment of Inertia	Minimum Cross Sectional Area	Minimum Outside Diameter or Square Width	Minimum Wall Thickness	*Example Sizes of Round Tube*
a.	Size A	11320 mm^4	173 mm^2	25.0 mm	2.0 mm	*1.0" x 0.095"* *25 x 2.5 mm*
b.	Size B	8509 mm^4	114 mm^2	25.0 mm	1.2 mm	*1.0" x 0.065"* *25.4 x 1.6 mm*
c.	Size C	6695 mm^4	91 mm^2	25.0 mm	1.2 mm	*1.0" x 0.049"* *25.4 x 1.2 mm*
d.	Size D	18015 mm^4	126 mm^2	35.0 mm	1.2 mm	*1.375" x 0.049"* *35 x 1.2 mm*

Figure 3.3.2: Chart from FSAE Rule Book showing the definitions of each tube size per Rule F.3.4.1

Color Codes are added to the tubes in the model for clarity; Size A (blue), Size B (yellow), Size C (red), Size D is not used and does not have a defined color.

When designing a steel tube frame, it is important to consider how it will be fabricated to ensure the process is as easy and inexpensive as possible. Welding convention is to start with a box structure and then fill in that structure with all the inner triangulation tubes. The frame can be divided in 4 separate box structures, the section forward of front hoop, the cockpit, the accumulator box, and the powertrain box. In addition, structures constrained to two dimensions are easier to weld than those in three-dimensional space. Therefore, an attempt was made to maximize the amount of tubes that can be welded in 2D to speed up the fabrication process.

Front Section

To begin, size B tubing is added to the Front Bulkhead's square structure to create the first planar structure. The Front Hoop, size A, with a portion of the floor, size C, can make up the second planar structure. The lower bulkhead support members, size c which also serve as the floor make up the last planar structure. The X Brace will complete the box structure, but it is not possible to add them as a planar structure.

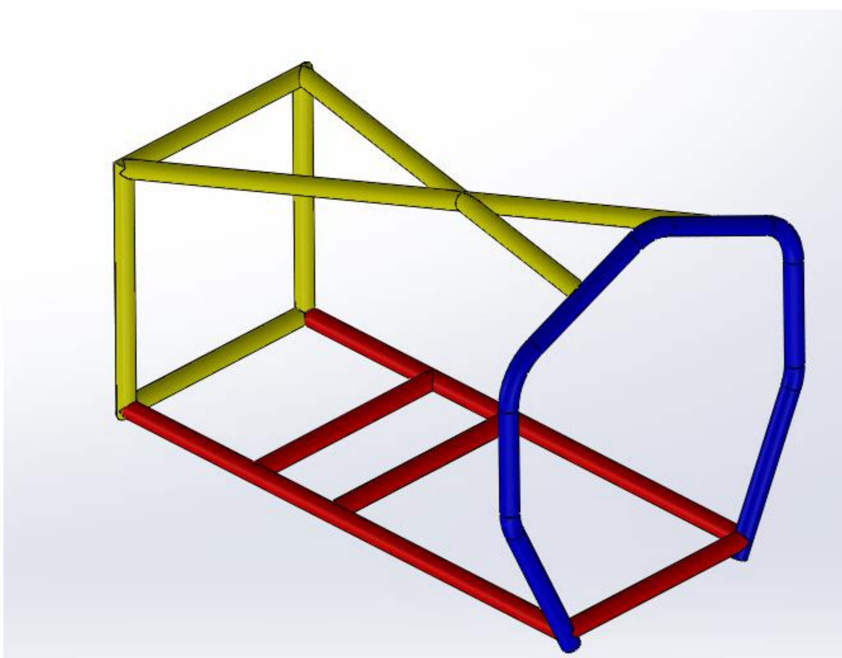


Figure 3.3.3: Isometric of front box structure of frame

Cockpit

The cockpit section is a little more complicated due to the angled member in lower SIS member which serves as cockpit floor. Due to the reference plane shown in Figure 3.2.4, the size B tubes that make up the cockpit floor meet at a flat angle and create a planar structure. In addition, the Main Roll Hoop, size A, including the 2 spars, size C, make up the second planar structure. The cockpit box is completed by adding in the size C tubes for the spar between both sides of the floor and the upper SIS member.

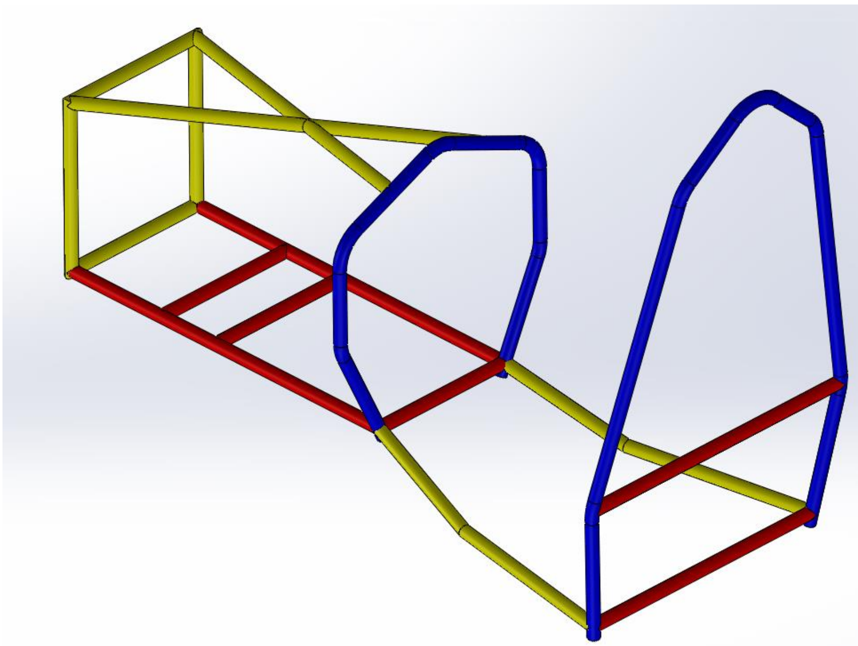


Figure 3.3.4: Isometric of front section of frame with cockpit's 2 planar structures

Accumulator and Powertrain Box

To give the motor a place to mount, an X brace added between the accumulator and powertrain box, details on why this configuration was chosen can be found in the Analysis and Testing section of report. The X brace is defined by the plane shown in Figure 3.2.7 which includes 6 tubes. Due to the number of tubes included and since this structure is critical to the mounting of the accumulator this structure is defined as a planar structure. The outer tubes are accumulator protection tubes and required to be size B while the inner tubes can be size C.

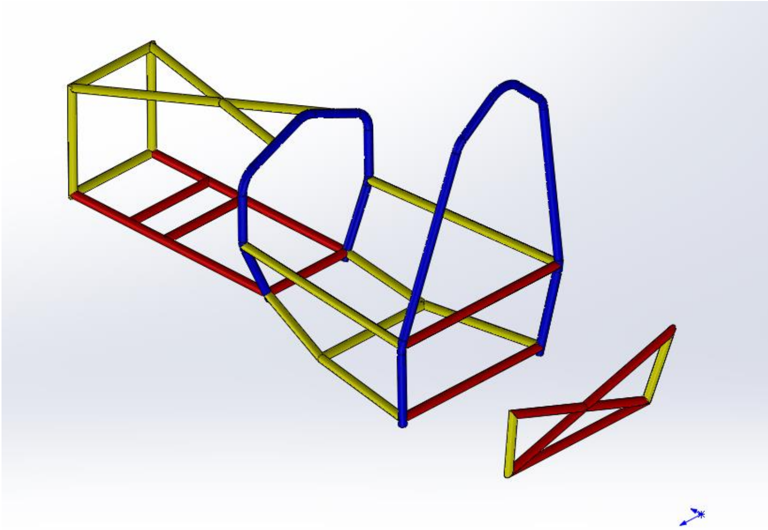


Figure 3.3.5: Isometric showing cockpit box structure and the planar structure of the X brace

The accumulator box can be completed by adding 4 size B tubes for the upper and lower accumulator protection members. Since the powertrain box ends at the rear of the frame, two planar structures can be used to create the floor and upper structure, Size C tubing is used since the powertrain box is not defined in any rules.

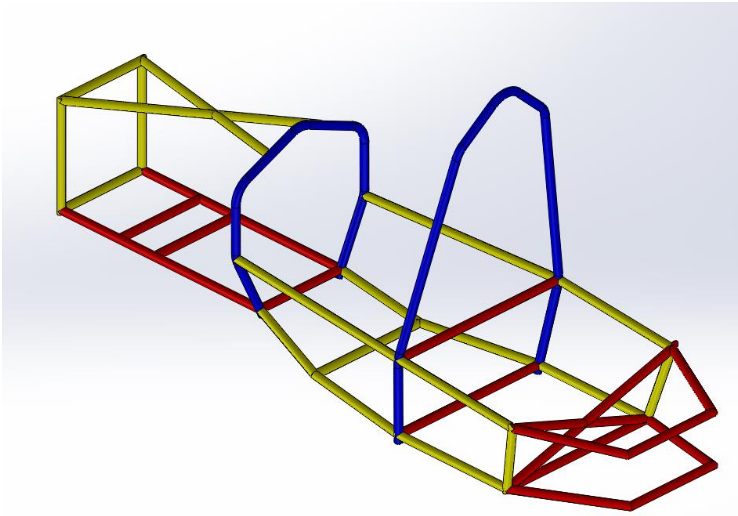


Figure 3.3.6: Isometric showing completed accumulator box and the 2 planar powertrain structures

The rear of the powertrain box can be completed with the addition of the two vertical tubes connecting the two planar structures.

Main Hoop Braces

With the basic lower structure of the frame complete, upper tube structures such as the Main Hoop Braces and supports can be added. Due to the angles that the braces and supports meet, an additional tube is needed for a strong connection to be made. This additional tube called a super node, is a short piece of thin walled tubing added to make tube notches easier and allow for a better attachment between multiple tubes. A size B tube is added for the hoop brace and size C tubes are added for the forwardmost and rearmost support members. These tubes meet at the super node, which is a 2" section of 1" OD tubing with .035" wall thickness

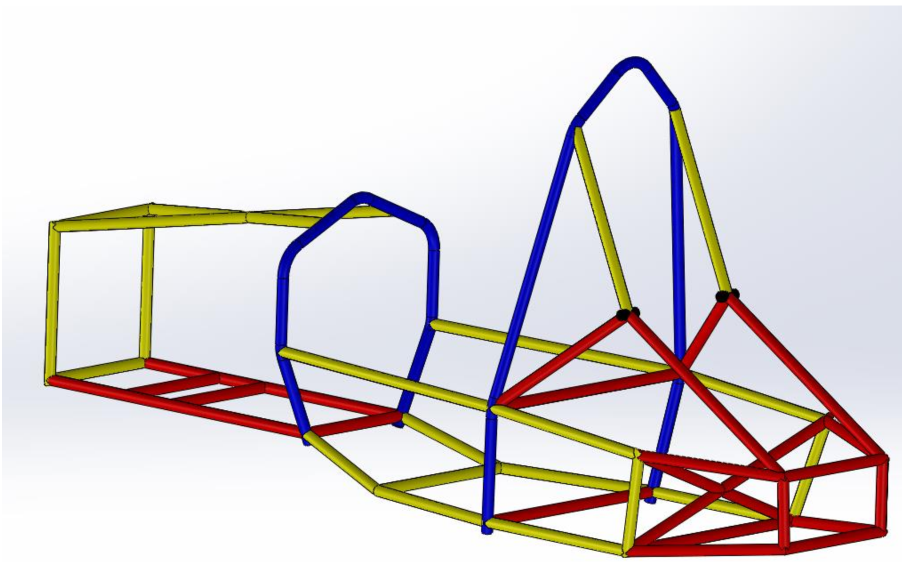


Figure 3.3.7: Isometric showing Main Hoop Braces and 2 of 3 Support tubes

With all the base box structures complete, the inside triangulation can be added for the main hoop supports, powertrain box, accumulator box and side impact structure. In addition, the shoulder harness bar (size A) and supports (size C) along with the head restraint tubes, .625" OD with .028" wall thickness, are added at this time.

Front Suspension Six-Star Member

The last section of the frame is the front suspension six-star members. This section of the frame is assembled last since the front suspension point, a critical point in the frame, is floating. With much of the frame assembled at this point, any warping of the frame from welding has already occurred. Therefore, when this structure is placed, its measurements and placement will be as accurate as possible. The lower three tubes can be defined as a planar structure using size C tubes since it is part of front bulkhead support structure.

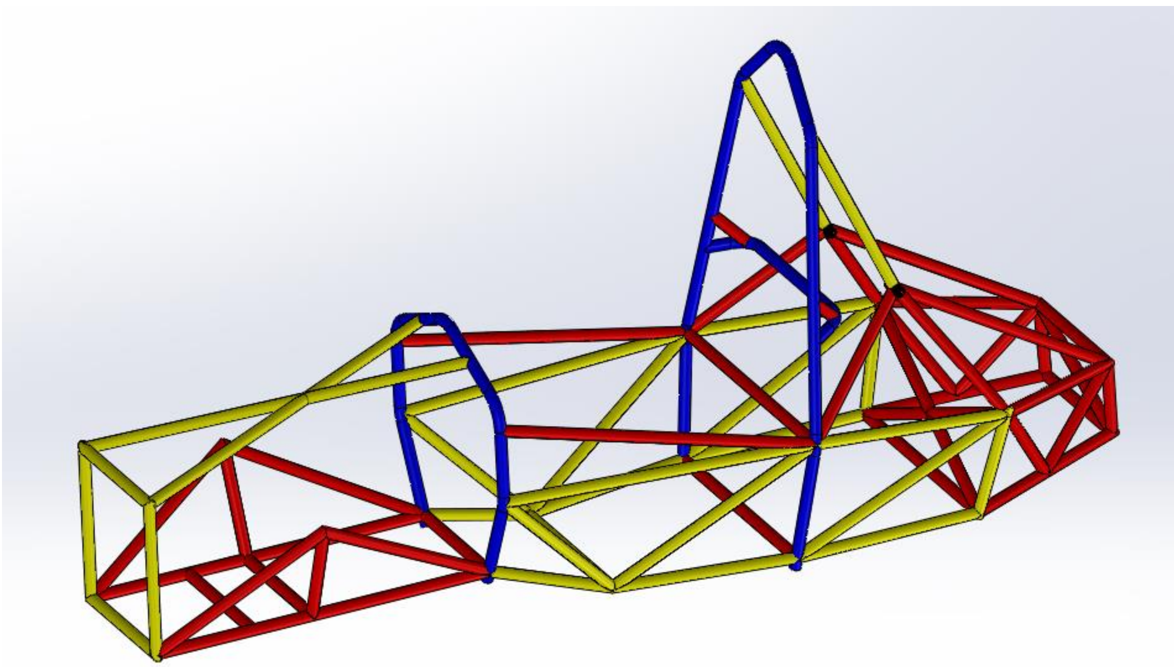


Figure 3.3.8 Isometric showing the planar structure for the lower 3 tubes from the Suspension six-star member structure

The remaining tubes in the six-star member are added from bottom to top to allow each tube to have firm attachment to the one preceding it.

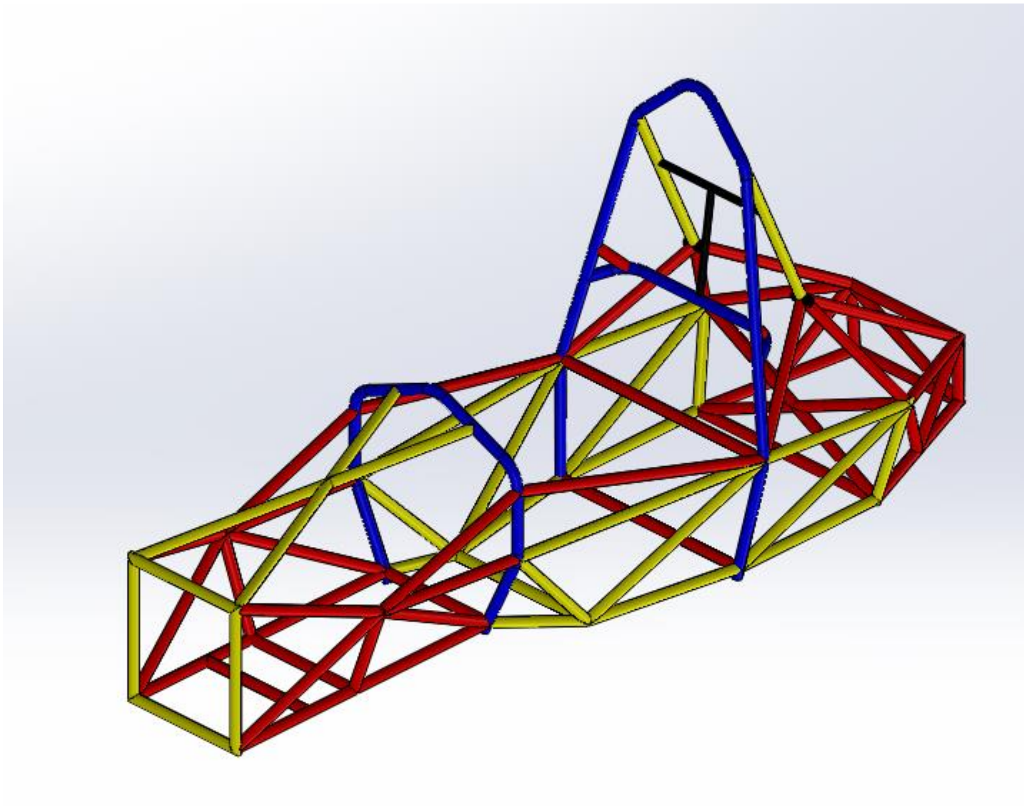


Figure 3.3.9: Isometric of the Completed Tube Model of Frame

While the initial design of the frame is complete, changes will be made as needed to support evolving component designs. The final design of the frame is based off the results of the FEA and the needs of the individual subsystems. Iterations were completed as subsystem parts were finalized and compromises were made to allow the vehicle to have the best performance overall. Many of these changes were minor either slightly changing the length of a tube or a location of a node. The FEA results that will be shown in the next section will optimize the frame's structure to provide the best stiffness to weight ratio while meeting all the needs regarding ZR20e's performance and the safety of the driver.

4 Analysis and Testing

An important parameter in frame design was torsional stiffness. The goal was to develop a frame with infinite torsional stiffness so that all factors contributing to the dynamics of the vehicle is solely based on tweaking the suspension parameters. As that is impossible, a compromise had to be made between frame weight and torsional stiffness.

$$s = \frac{Fr}{\tan^{-1}(\frac{\delta}{d})}$$

Figure 4.1: Torsional Stiffness Equation

Where s is the torsional stiffness, F is the force applied at the center of the front uprights, r is the distance between the center of the upright to the midplane of the frame, δ is the upward(or downward) deflection at a point on the frame, and d is the distance between the point and the midplane of the frame. The analysis below was modeled to simulate a physical torsion test.

4.1 Torsional Stiffness FEA

FEA using SolidWorks was used to optimize the tube structures under the MRH and at the Powertrain Box. The analysis model was created with the following parameters. All the tubes were modeled as beam members except the super nodes and harness bar supports which had to be modeled as solids due to their short length. The material was set as AISI 4130 Normalized Steel for all beams and solids in the model. A bonded global contact was used to simulate the welded joints, the joints created between the control arms and the frame, and the joints between the control arms and the uprights. The uprights were modeled as steel tubes with the same profile as the control arms because the suspension components were not yet modeled

The rear uprights were fixed while an equal and opposite force of 1750 N was applied to the center of the front uprights, creating a force couple. In a physical torsion test, the rear uprights are fixed using fixtures while a moment in the front is generated using something that produces force such as hanging weights or using a floor jack etc. A gravitational force was also applied at the center of mass.

A blended curvature-based mesh was used due to lack of convergence for the standard mesh and the curvature-based mesh. The blended curvature-based mesh is prone to higher aspect ratios which reduces the accuracy of the simulation and will be discussed below. The maximum element size was 0.083in, the minimum element size was 0.083in, the minimum number of elements in a circle was the default at 8, and the element size growth ratio was the default at 1.5. These settings coincide with a “fine” mesh.

A mesh quality plot was generated to view the aspect ratio of the mesh and can be found in Appendix A. Overall, the average aspect ratio was about 2.10 which is close to 1 and indicates a good mesh. A high aspect ratio means that the element’s shape is distorted which tends to create error in the simulation There were a few areas between the MRH and the harness bar where the aspect ratio was upwards of a 100 and in one place, a maximum of 478. Many efforts including trying different meshing techniques and applying a mesh control to reduce the element size on the MRH were tried to reduce the aspect ratio, but nothing worked. A physical test was warranted to validate the FEA to determine if the aspect ratio was skewing the deflections.

From the results of the simulation, a displacement in the Z direction was found near the center of gravity using the probe tool and can be seen in Appendix A. Due to the equal and opposite force applied, the simulation showed the right side of frame having a negative displacement while the left side was shown to have a positive displacement as expected. The displacements between each side were not perfectly symmetrical and some suggestions as to why are the mesh is not perfectly symmetrical, the high aspect ratios may be skewing the results, the frame model is not completely symmetrical (in the rear crash structure) and overall, the frame might not be completely symmetrical due to modeling error. Inputting the displacements from the simulation into the equation, the torsional stiffness was found to be 1358 Newton meters per degree for ZR20e.

FEAs were ran for several configurations of ZR20e and for ZER-19 which can be seen in Appendix A. Some configurations were better than the selected one when compared using the stiffness over weight ratio, but were not chosen due to packaging concerns. Configurations ZR-20e –3, ZR-20e –4, and ZR-20e –6 was better than the chosen configuration, ZR-20e-7, in terms of the torsional stiffness versus weight ratio, but those three configurations made accessing the accumulator difficult.

A FEA using the same settings and parameters was ran for ZER-19 to compare the torsional stiffness between the new frame and the old frame. An aspect ratio plot was generated for the ZER-19 which can be found in Appendix A and also had the high aspect ratio problem at a max of 3140. The average aspect ratio was 3.09 which indicates an overall good mesh. The torsional stiffness was found to be 1306 Newton meters per degree.

The torsional stiffness for ZR20e was 3.92% higher than ZER-19's and had a 10% decrease in weight. The reason ZR20e was stiffer while being lighter was because ZR20e was better triangulated, and the track width was shorter which created a smaller moment arm when the frame would undergo twisting.

4.2 Physical Testing of Frame for Torsional Stiffness

Design

A torsion test rig was designed to validate the torsional stiffness from the frame analysis. The torsion test's fixtures were designed such that the car would be at ride height during the test. The front torsion rig consisted of two bearings, a beam, a shaft and two fixtures. The two fixtures were manufactured specifically for ZR20e while the beam, shaft and bearing assembly was borrowed from Zips Electric Racing. The two fixtures would bolt onto the beam while the bearings would bolt to the table. The fixtures consisted of a top portion and bottom portion. The top portion had counterbore holes that would line up with the hubs and two bottom counterbore holes that would line up with bottom portion of the fixture. The bottom portion had two tapped holes on the side to screw into the top portion of the fixture and a milled counterbore slot to allow for versatile placement of the fixture.

The rear torsion rig only consisted of a beam and two fixtures. The fixtures would also bolt to the beam while the beam would bolt to the table. The rear fixtures also consisted of a top portion and a bottom portion where the bottom portion was universal between the front and rear top portions. The rear top portion was almost identical to the front top portion except the location of the counterbore holes for the hub and the overall height.

The front beam had a rod sticking up where a weight bucket would hang and create a moment on the frame. The bearings allowed the frame to twist in the front while the rear remained fixed. The deflection of the frame would then have been measured at certain predefined points using dials and torsional stiffness would have been calculated.

Manufacturing

From the engineering drawings from the design of the torsion rig, two front fixtures, two rear fixtures, and four bottom fixtures were manufactured using a band saw, drill press, and manual mill. Each fixture was cut to the specified length using the band saw. Then, the bolt and screw hole patterns were marked using Dykem to ensure accuracy when drilling. Prior to drilling the holes, a center drill was used on the front and rear fixtures to further improve accuracy. When drilling the bolt patterns, two fixtures were clamped together, and all twelve holes were drilled at once. Next, a counterbore was used to fit the socket head cap screws. The holes were for the bottom fixtures were drilled and tapped individually. After all the hole patterns were drilled and tapped, a mill was used to create a counterbored slot in the bottom fixtures.

4.3 Validation of Driver Headrest

Per Rule T.2.8.5, The headrest and all of the headrest assembly components had to withstand a 900 N rearward applied force in one case, a 300 N lateral force applied in another case, and a 300 vertical force applied in another case. SolidWorks Simulation was used to validate the headrest assembly.

The headrest assembly consisted of the plate, two collars, 4 bolts and nuts, 8 washers, the harness bar and harness bar support, and the two tubes making up the support of the headrest. The plate was made of 6061 Aluminum, the tubes were made of 4130 Normalized Steel, and the fasteners and collars were made of 1020 Steel. The harness bar tubes were modeled as beams while the washers, headrest tubes, bolts, nuts, and plate were modeled as solids.

The default contacts were to set to bonded and all contacts were bonded except between the horizontal tube and the plate and the vertical tube and the plate which were set to a no penetration contact. A bonded contact behaves as if the bodies are welded, so the stiffness was overestimated. The no penetration contact is more accurate from a physics perspective since the bodies would not behave as welded, but the solution would not converge when all contacts except for the bolt and nuts, which were set to a bonded contact to simulate threads, were set to no penetration. Also, the no penetration contact requires exponentially more computational power than the bonded contact which makes the bonded contact a necessary simplification (Changing the no penetration contact for the vertical tube and the plate and the horizontal tube and the plate above to bonded makes the simulation go from 45 minutes to 10 minutes).

A curvature-based mesh was used with these overall mesh settings: a maximum element size of 0.416in, a minimum element size of 0.0832in, a minimum of 8 elements in a circle, and an element growth ratio of 1.6. Mesh controls were applied due to mesh failures for the collars and the two headrest tubes were implemented. The mesh control for the collars had an element size of .185in and an element growth ratio of 1.5 The mesh control for the vertical headrest tube had an element size of 0.100in and an element growth ratio of 1.5. The mesh control for the horizontal headrest tube had an element size of .0925in and an element growth ratio of 1.5.

A force of 900 N was applied in the rearward direction to the face where the headrest pad would go. For the other cases, a 300 N for was placed on the top face of the plate acting downward for the vertical case, and a 300 N force was applied on the right side of the plate acting towards the plate for the lateral case. A gravitational load was also applied, and the bolts were set to a preload of 2 Nm, which is the preload for #8 bolts. The ends of all the tubes that would go into the rest of the frame were all fixed.

A mesh quality plot was created, and factor of safety plots were created to determine if the headrest assembly would fail in any of the three cases. These plots can be seen in Appendix A. The mesh quality plot indicated that the maximum aspect ratio was 22.3. The average aspect ratio was 3.69 which indicates a good mesh.

For the rearward case, the lowest FOS was .587 and was found around the intersection of the vertical tube and harness bar. Normally, a FOS of less than 1 indicates failure will occur but the low FOS was along where a weld fillet would be which would decrease the stress along that area and prevent failure. The lowest FOS for all the other components was 1.61 which indicates the headrest assembly will not fail even if the stiffness is overestimated. For the vertical case, the lowest FOS was 2.20 and for the lateral case, the lowest was 2.93. The headrest has now been validated using FEA.

5 Manufacturing

5.1 Tube Fabrication

One of the main considerations of the frame design was to make fabrication as quick as possible. The fabrication begins with exporting the full weldment of the frame model seen above and converting it into its base parts. 83 tubes make up the frame and each of them must be made into an individual 3D model for fabrication.

CNC laser profiling technology was utilized to ensure each tube notch was made as accurate as possible to the model. Each individual tube's 3D model was converted into a CNC code which guided the laser tool that cuts and notches each tube. The profiling of our tubes was provided at a discount from Miterworks, a local company in Kent, Ohio.

In addition, the frame model included three tubes that required bends. The Front and Main Hoop both required 5 bends and the Driver Harness Bar required 2. For each of these tubes the bends were all in the same plane and were designed to have a 3" center line radius (CLR) as shown in Appendix D. Due to the number of bends needed on the roll hoops, CNC tube bending was required. Like CNC laser profiling, the 3D model of each tube is converted into a CNC program that accurately bends the tube to exactly match the model within the specified tolerance. CNC bending was used over other techniques because of the high accuracy and the ability to create tubes with more than 3 bends. The bending of the three tubes was provided as a full sponsorship by NC Chassis, a local company in Tallmadge, Ohio.

Once the tubes were bent, the tubes were laid out on the one to one scale printouts shown in Appendix E. The accuracy of the bends was then assessed to make sure the tubes were symmetrical, and the bends were in the right location. Adjustments were then made to account for the addition of the hoop spars. The bend radii were not critical, but the location of the bends was critical since the tubes were designed to mount in the middle of the bends.

5.2 Welding

This frame like any complex 3D welded structure requires a system of welding fixtures to place tubes in a defined location in space to ensure accuracy. The 8' x 4' welding table in the Student Design Center defines x and y coordinates using a 12" x 12" inch grid etched into the surface. The front suspension reference plane is defined to be coincident to the short side of the welding table and the midplane is defined to be coincident to the midplane of the long side. Welding fixtures are used to position tubes along the z axis. The frame has 3 different levels and therefore requires 3 unique fixtures. One for the front section, one for the lower cockpit and accumulator box, and one more for the rear crash structure. Each of these fixtures were precision machined using a mill to meet the specific tube when the car is at the neutral ride height. Each fixture has a ½" radius milled at the top to allow the 1" OD frame tubes to nest perfectly inside. The drawings for these fixtures can be found in Appendix F. To ensure the frame was adequately constrained, 5 fixtures were used for the front section, 7 for the cockpit, and 2 for the rear crash structure. In addition, a fixture was needed to ensure accurate placement of the super node and the four tubes that attach to it. This fixture was designed from 2 lengths of square tubing welded together in a T formation. A metal slug was designed to slide into the super node and bolt to the fixture at the required z coordinate and be positioned on the table using the grid. The drawings for the super node fixture can also be found in Appendix F.

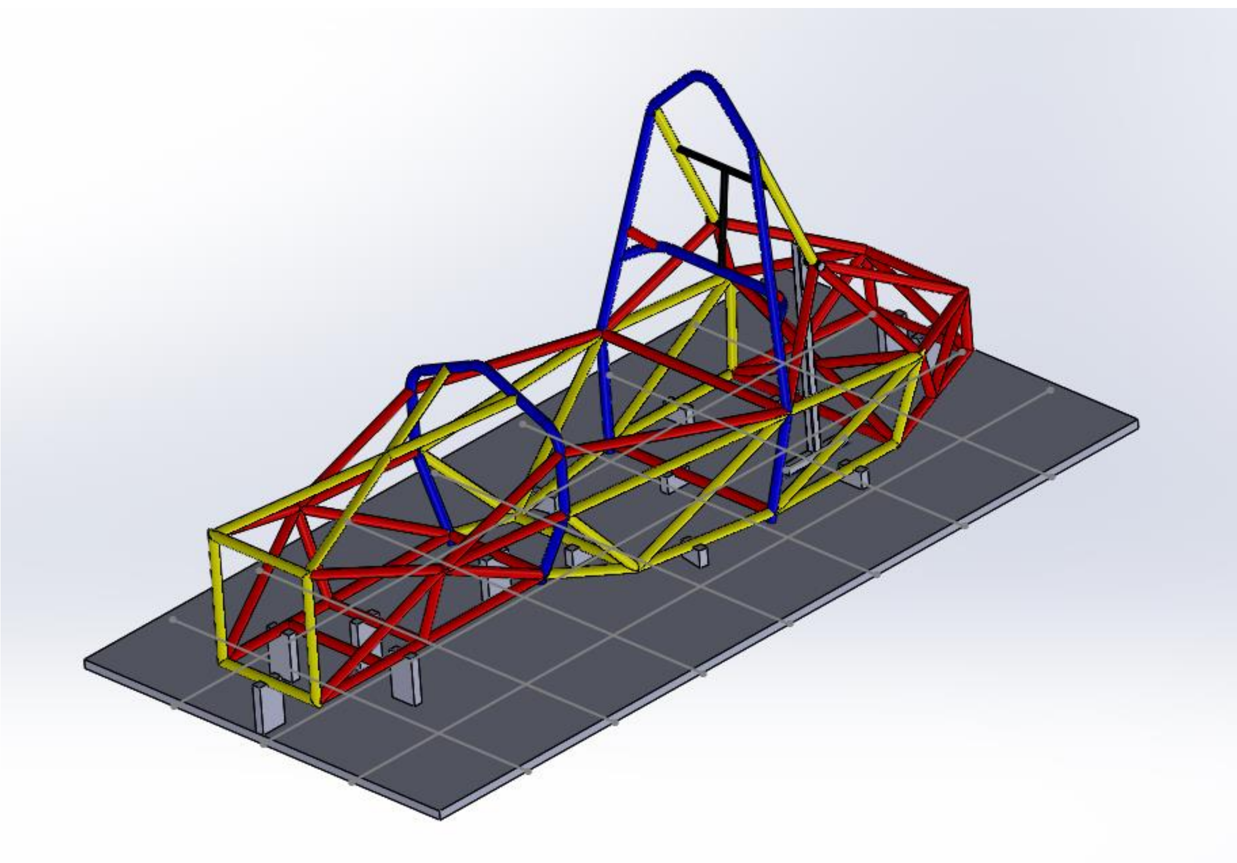


Figure 5.2.1 Final Frame on Welding Table with Fixtures

Fabrication Process

To start manufacturing, large one to one scale printouts of the planar structures were made. These printouts will be used as a template to place the tubes in their defined locations. The manufacturing sequence is the exact same as the process outlined in the Tube Model section of the report. Each vertical planar structure, the Front Bulkhead, Front Hoop, Main Hoop, and Accumulator X brace have their midpoint marked so that they can positioned accurately along the Y axis on the welding table. To position the tube structures along the x axis, the tangent of the lowest tube is extended down to the welding table and a measurement is taken. Calipers and a square tool are used to transfer that measurement to the welding table in order to position the tube structure. After the planar structures are positioned on welding table, an angle gauge is used to verify their angle to the top of the welding table.

The super node is positioned in a similar fashion except the measurements are taken from the fixture and both X and Y coordinates are needed. The fixture is clamped to the table and each tube is held in position and welded. The lower planar structure of the 6-star member is positioned using by extending a tangent line from the top node down to the welding table. This location is marked on the table and a plumb bob is used to verify when the location is reached. This method is used over an angle gauge since the location of this node is more critical than it being at the correct angle. After all the planar structures were assembled and welded together, each remaining tube was placed and held in position while it was welded.

6 Conclusion

The design of the ZR20e frame began with the creation of targets based on the team's goals for the new car. Once the targets were established, basic conceptualization and modeling started to get a general idea of the frame structure. Suspension points from last year's model allowed basic geometries and configurations to be defined while new points were modeled and analyzed to achieve optimal vehicle dynamics. Throughout the fall semester, the frame was slowly refined as the subsystem teams completed and finalized their designs. Concurrently, the full frame was analyzed using FEM to optimize the tube configurations to ensure the lowest weight and the highest stiffness that could also support the needs of the subsystem while also keeping the driver safe.

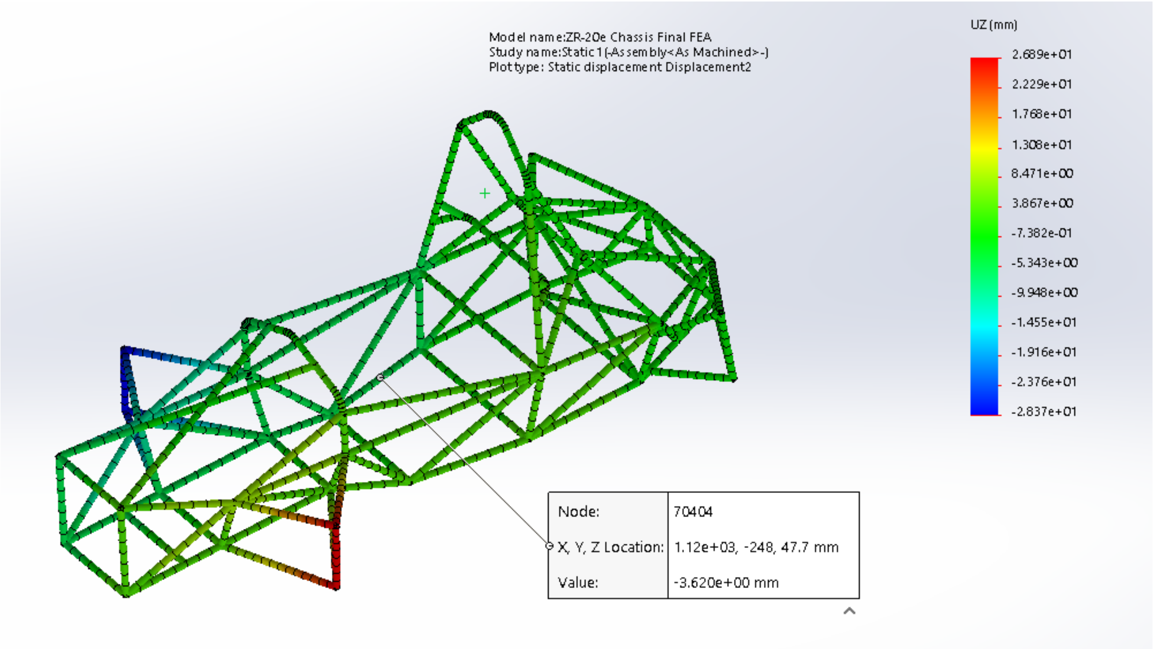
After the frame design was complete, manufacturing began with the fabrication of the individual tubes using CNC tube bending and notching. Frame fixtures were also designed and manufactured to ensure that the tubes could be placed exactly where they were in the model. When tube fabrication concluded, the tubes were surface prepped and the welding of the 2D structures began by utilizing the 1:1 printout. Over winter break, the frame was fully welded and ready for the next step. Pictures of the frame during and after manufacturing can be found in Appendix H. Fixtures for a torsion test for ZR20e and ZER-19 were designed and manufactured at this time. A torsion test was planned for the frames to physically confirm the torsional stiffness measured in SolidWorks Simulation. Unfortunately, this test was not able to be completed due to world events. While we could not complete the physical torsion test, it would be a useful metric for revisions of this frame by future teams.

Based on the insights gained from designing this year’s model, it is important to discuss improvements that can be made by future Zips Electric Teams. An important note that can improve the production of the car is to modify the rear frame to avoid offset nodes and simplify the main hoop brace structure. The current configuration makes placement for welding challenging and leaves production open for human error. Another suggestion would be to use composite materials to further reduce weight and increase stiffness. While the ZR20e frame did not utilize composite materials, there is limited room for more optimization with a full steel tube space frame due the constraints of FSAE rules. Future teams should consider the use of composites materials either partially with a hybrid frame design or with a full composite monocoque to further reduce weight and optimize further.

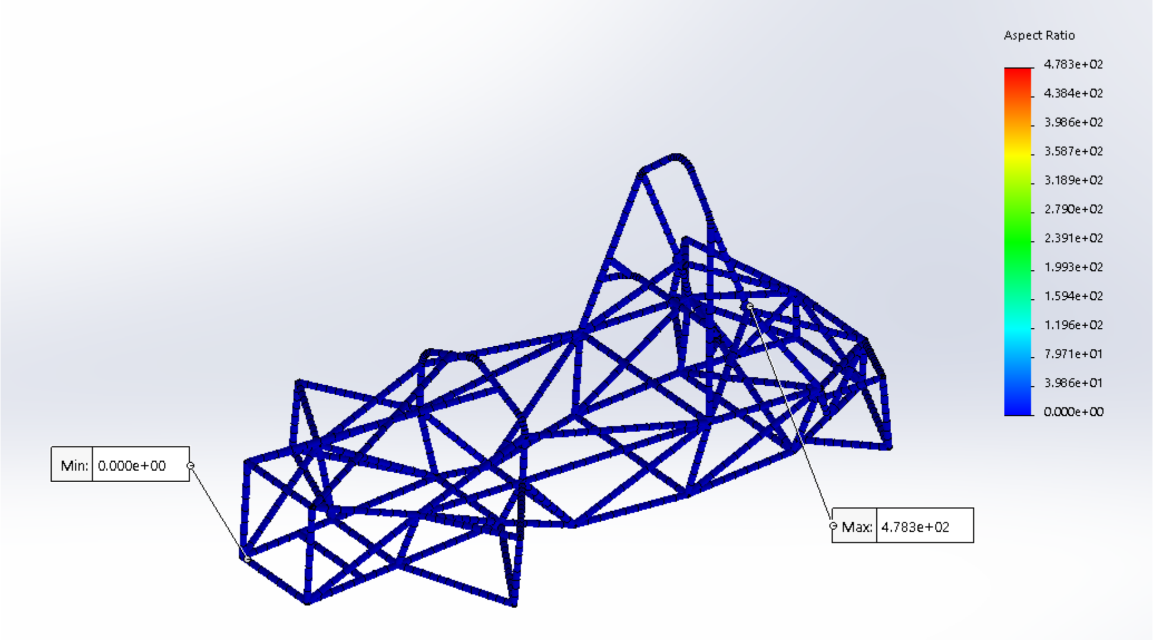
Overall, the ZR20e frame was a substantial improvement over the ZER-19 frame. Each goal set by the team was accomplished. This year's frame had a 10% reduction in weight and 3.92% increase in torsional stiffness compared to the previous year. The number of tubes was reduced by 15 with less unique tube sizes. The driver seat angle now sits 11° more vertical than the previous year which improved driver comfort. While ZR20e has not been completed at the time of writing this report, it can be said with confidence that the improvements made to the frame will result in a more competitive racecar.

7 Appendix

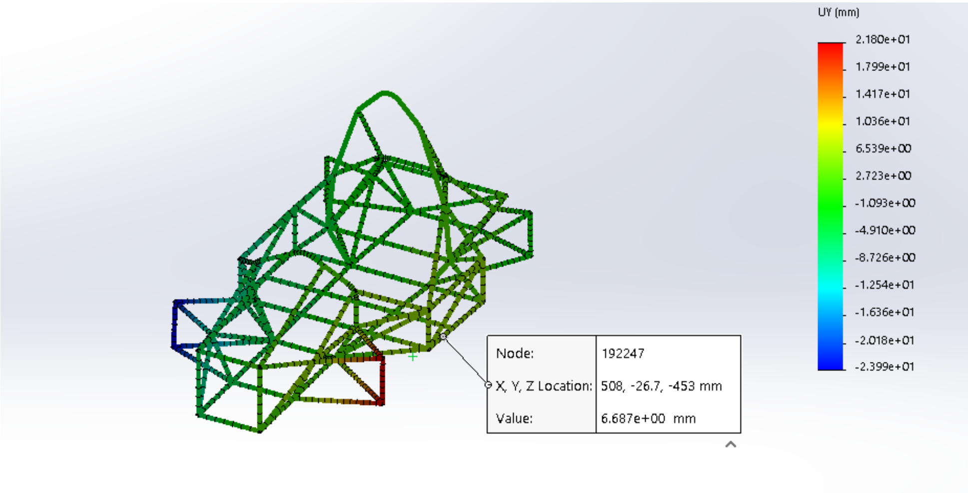
Appendix A: Torsional Stiffness FEA Results and Plots



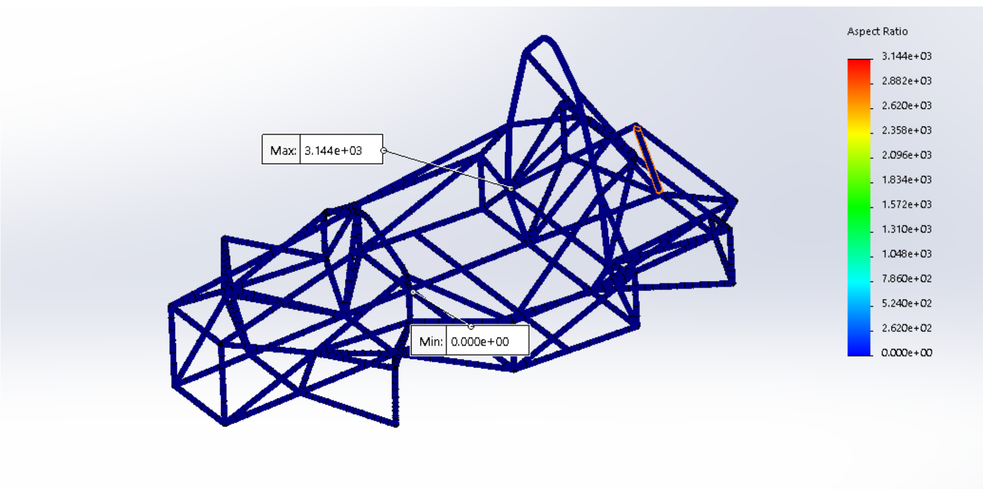
Deflection of ZR20e Frame



Mesh Quality Plot of ZR20e Frame



Deflection of ZER-19 Frame

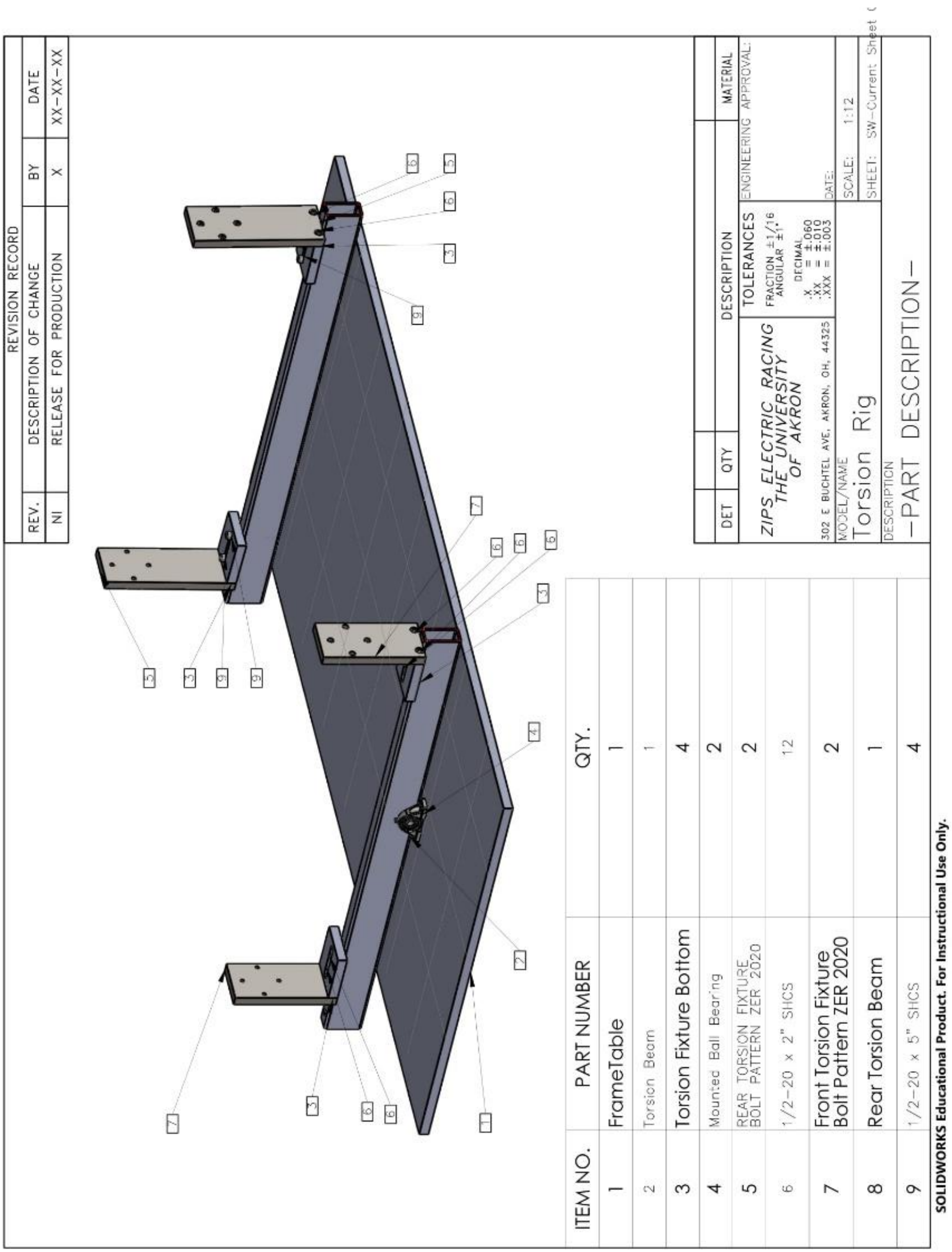


Mesh Quality Plot of ZER-19 Frame

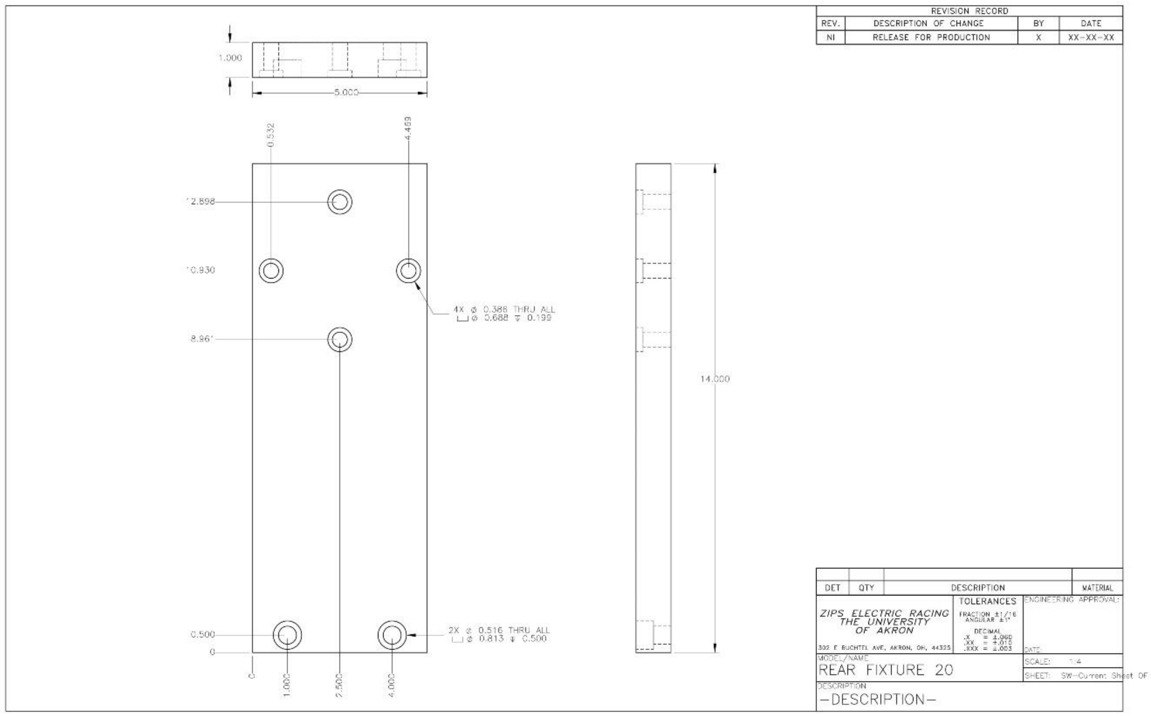
Configuration	Weight (lbs)	% Weight Change	Torsion Stiffness (Nm/deg)	% Change Stiffness	Stiffness/ Weight	Triangulation		
						MRH	PowerTrain Box	Rear Crash
ZR-19	91.07	0.0%	1306	0.00%	14.35	N/A	N/A	N/A
ZR-20-1	75.87	-16.7%	1277	-2.25%	16.83	Upper only	Upper	Up to Left Tri
ZR-20-2	76.89	-15.6%	1309	0.22%	17.03	Upper only	Upper + Up Left Brace	Up to Left Tri
ZR-20-3	78.93	-13.3%	1377	5.41%	17.45	Upper + X Brace	X Brace	Up to Left Tri
ZR-20-4	77.92	-14.4%	1365	4.50%	17.52	X brace only	X Brace	Up to Left Tri
ZR-20-5	76.86	-15.6%	1317	0.81%	17.13	nothing	X Brace	Up to Left Tri
ZR-20-6	77.89	-14.5%	1374	5.17%	17.64	Upper + Up Left Cross	X Brace	Up to Left Tri
ZR-20-7	77.87	-14.5%	1358	3.92%	17.44	Upper	X Brace	Up to Left Tri

Torsional Stiffness Comparison Between ZER-19 and Various Configurations of ZR20e

Appendix B: Torsion Rig Drawings



Torsion Rig Assembly Drawing



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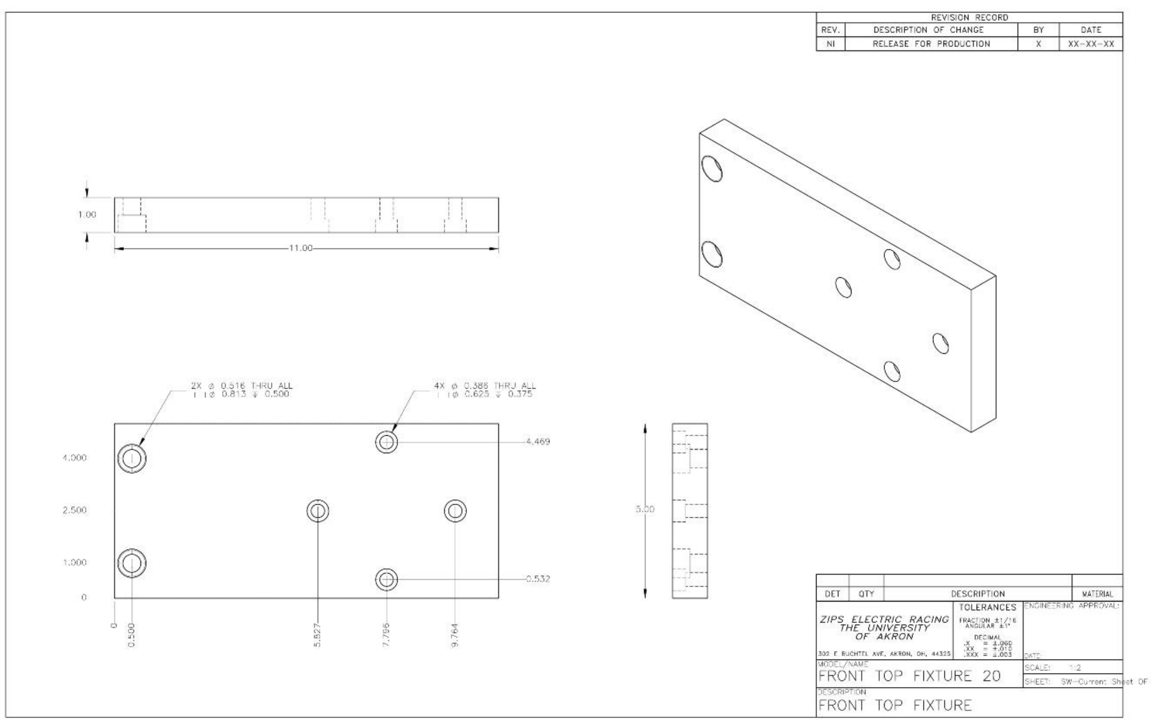
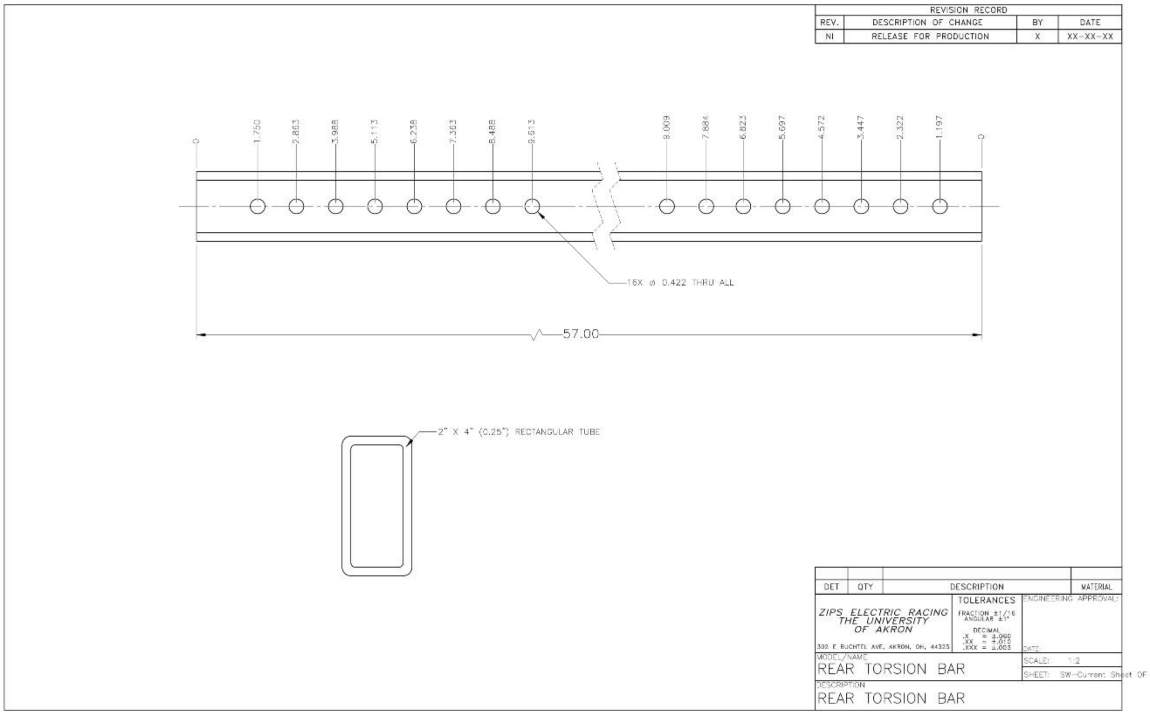


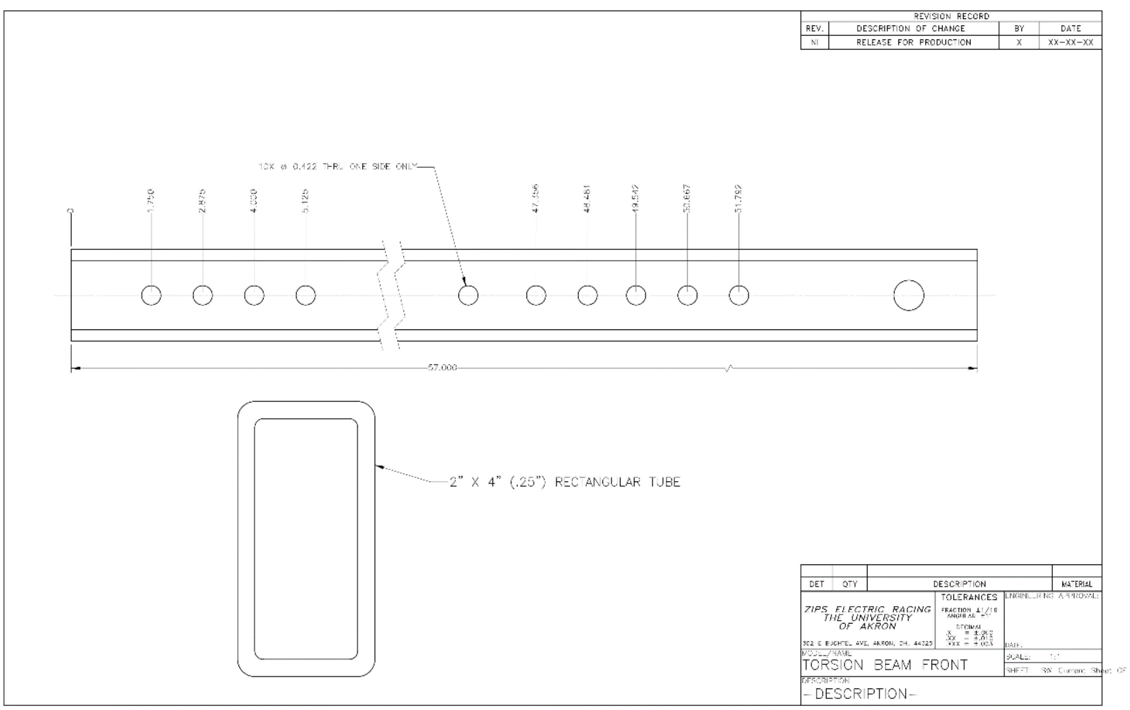
SOLIDWORKS Educational Product. For Instructional Use Only.

Front Upright Fixture



SOLIDWORKS Educational Product. For Instructional Use Only.

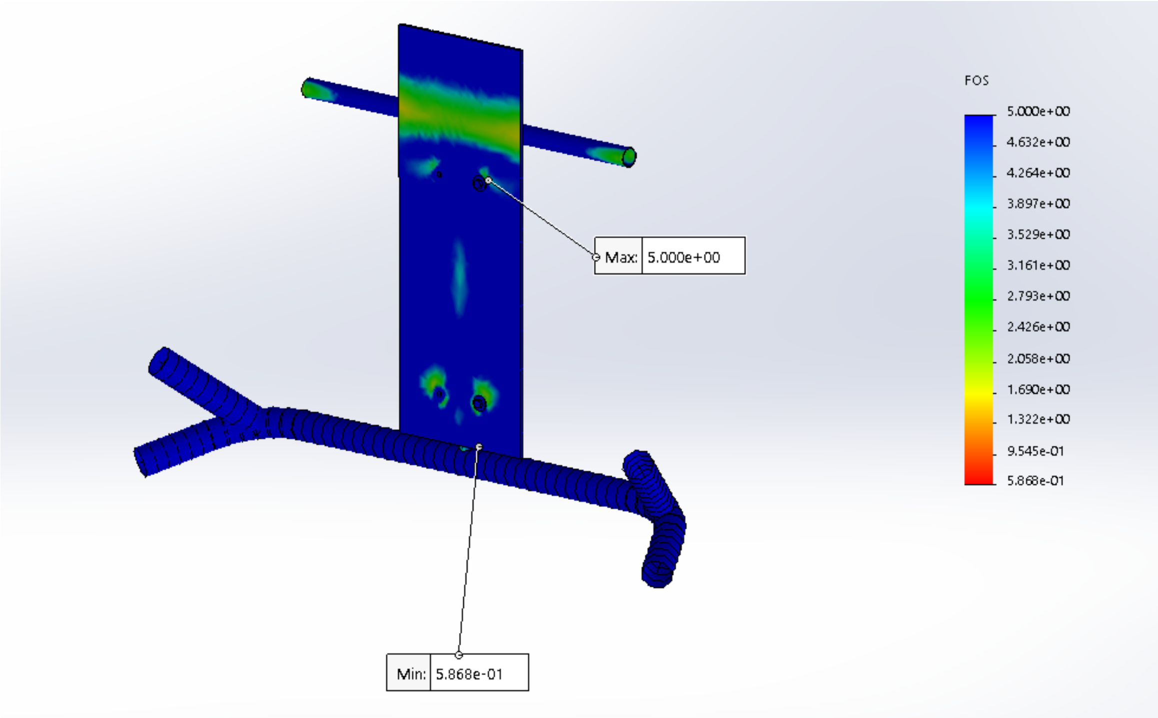
Rear Torsion Beam



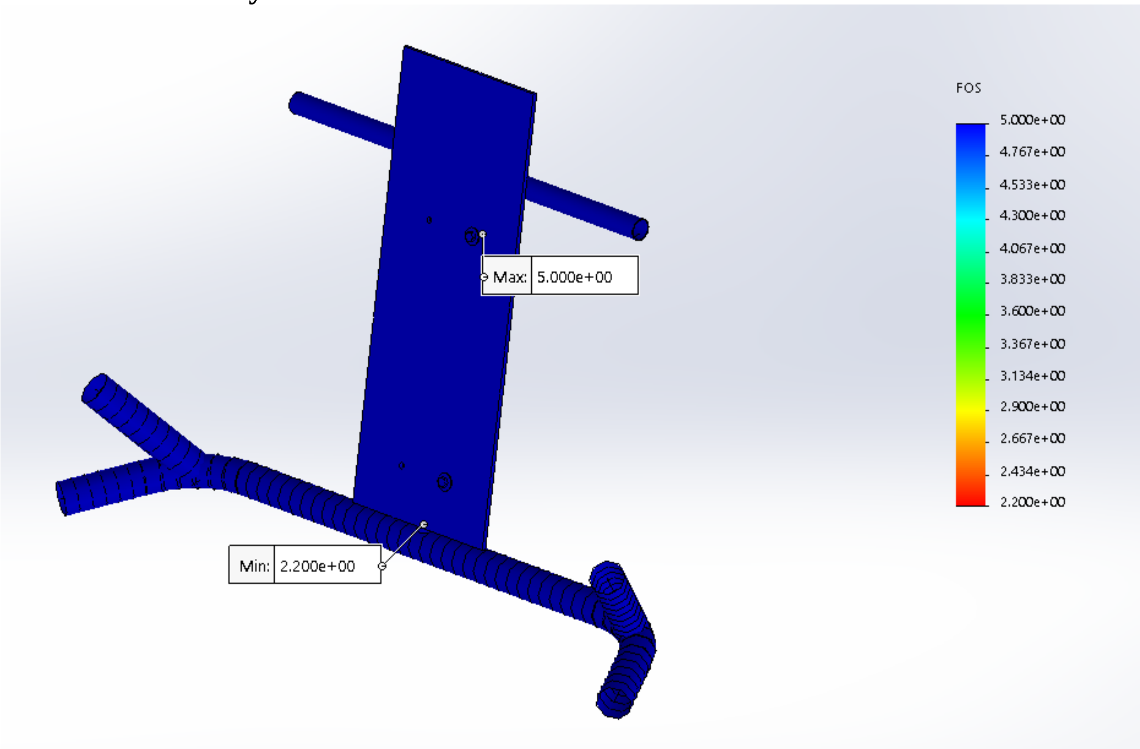
SOLIDWORKS Educational Product. For Instructional Use Only.

Front Torsion Beam

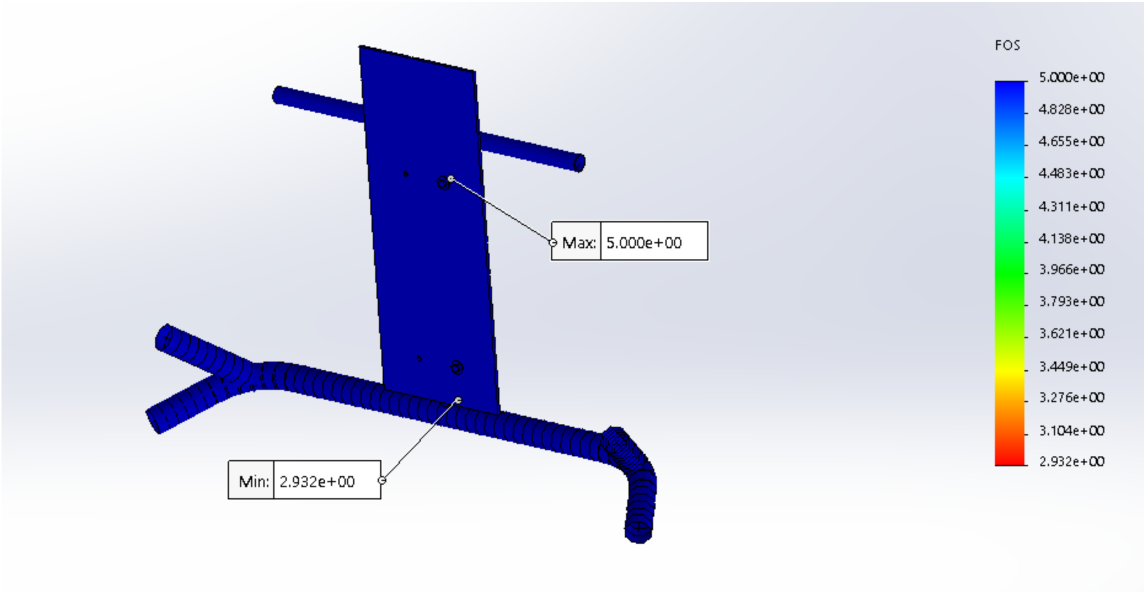
Appendix C: Headrest Validation FEA Results and Plots



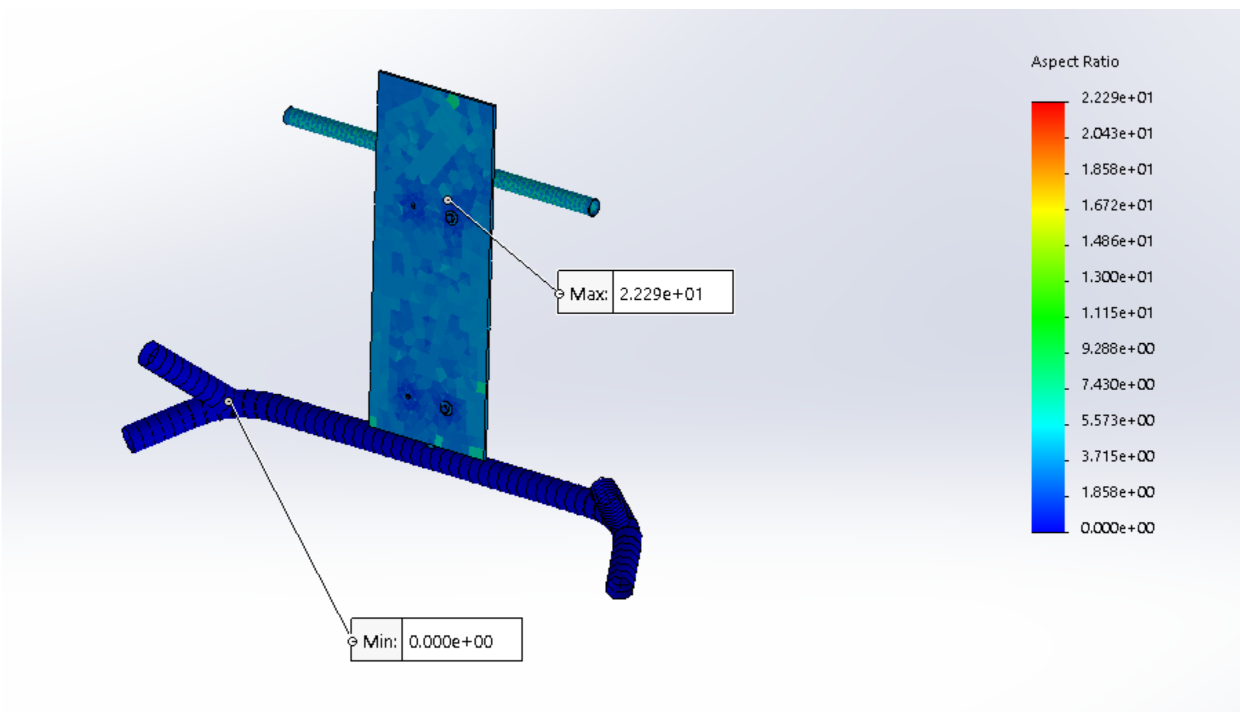
Headrest Assembly – FOS of Rearward Force Case



Headrest Assembly – FOS of Vertical Force Case

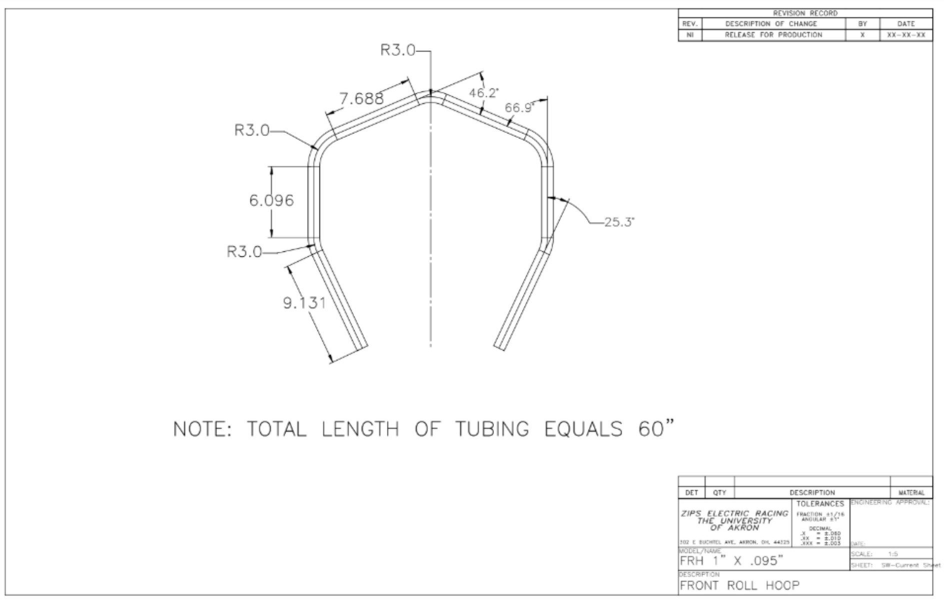


Headrest Assembly – FOS of Lateral Force Case

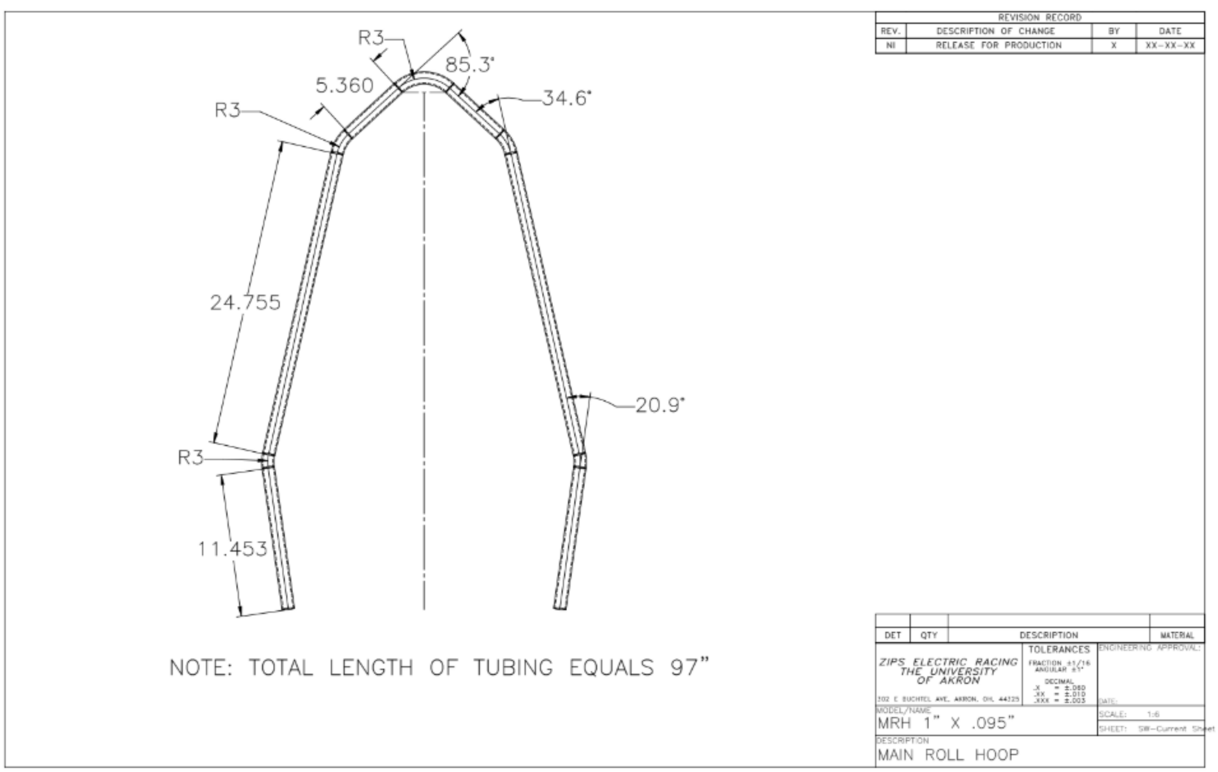


Mesh Quality Plot of Headrest Assembly

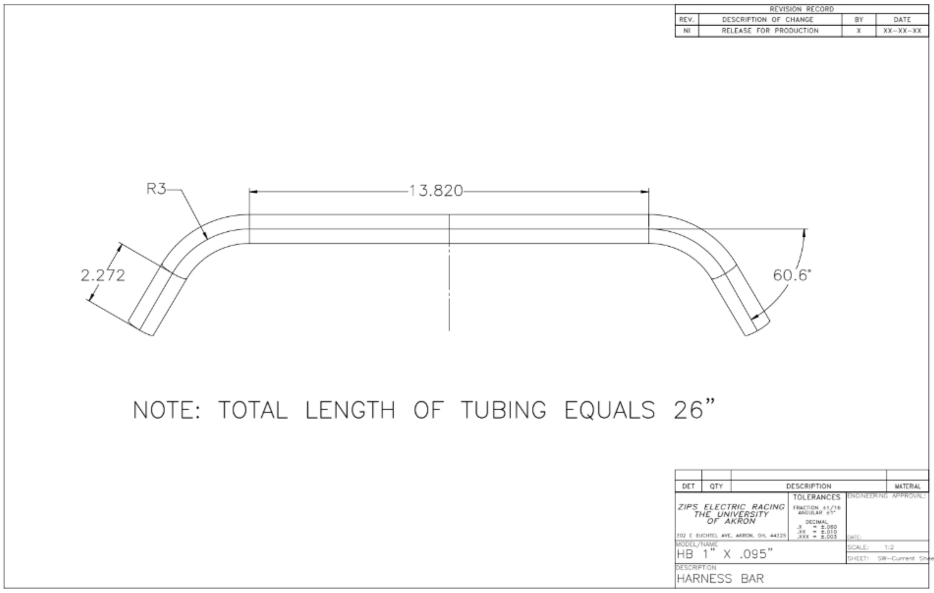
Appendix D: Tube Bending Drawings



Front Roll Hoop Drawing



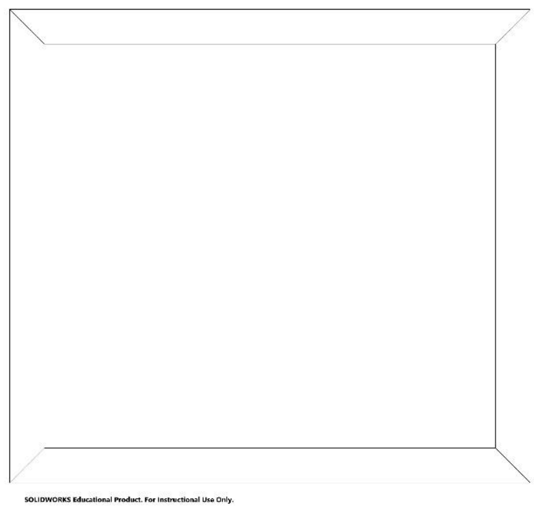
Main Roll Hoop Drawing



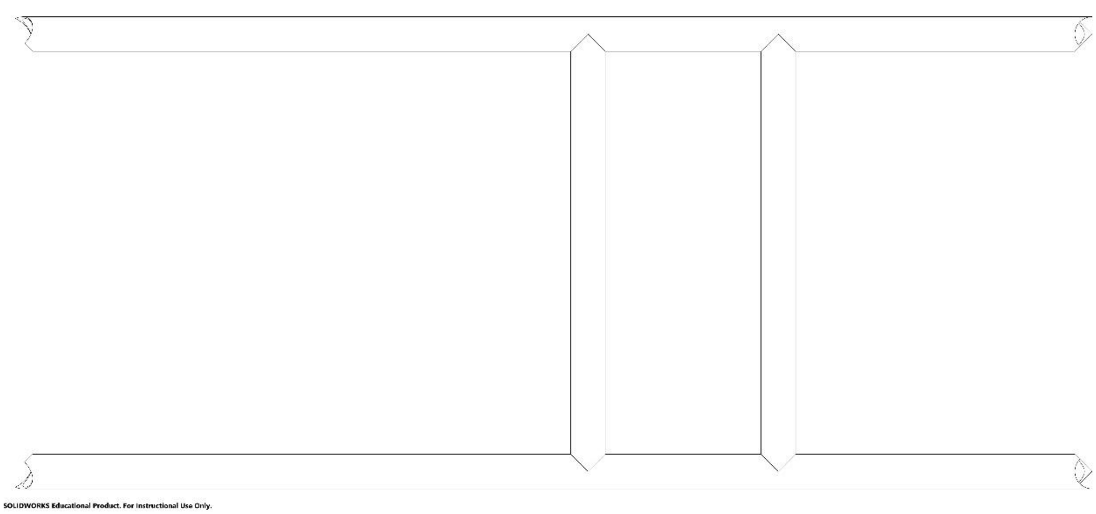
Harness Bar Drawing

Appendix E: 1 to 1 2D Template Drawings

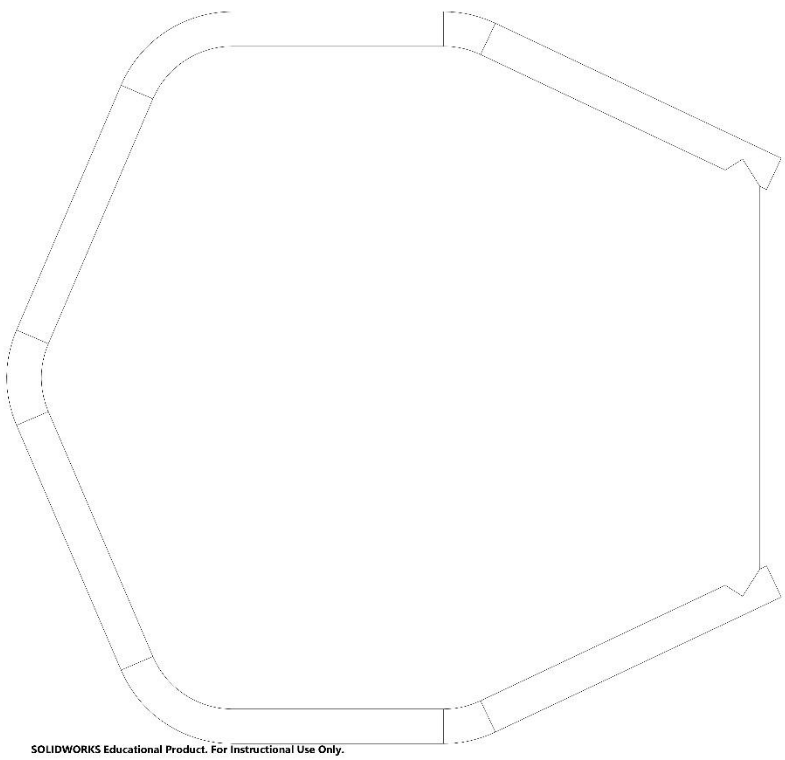
Front Bulkhead



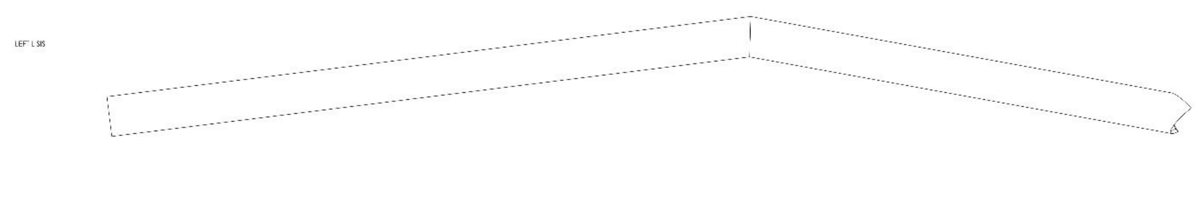
Front Floor



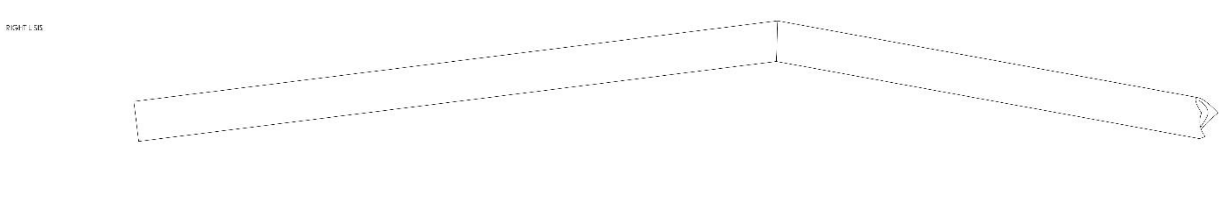
Front Roll Hoop + Spar



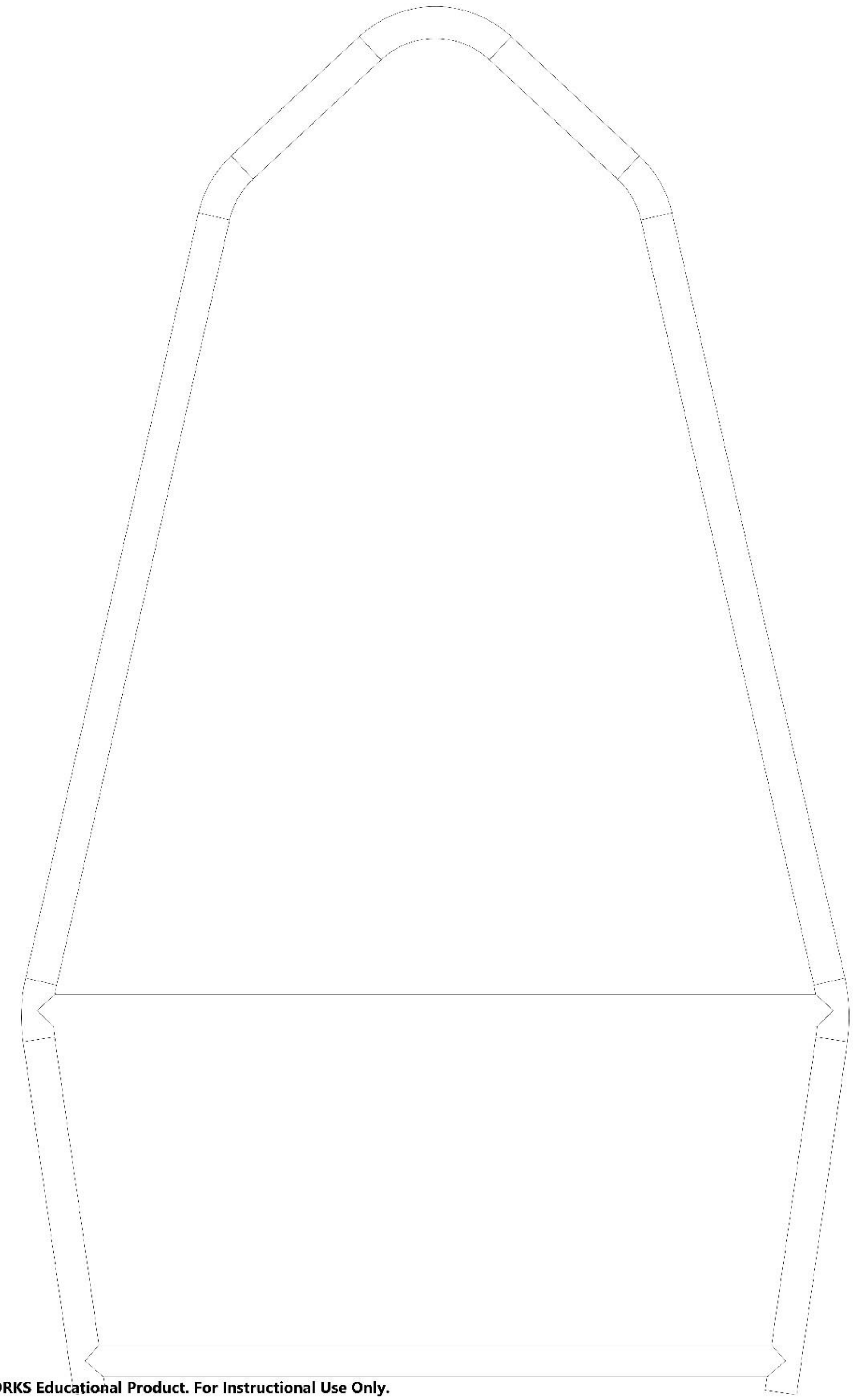
Lower Side Impact Member (Left)



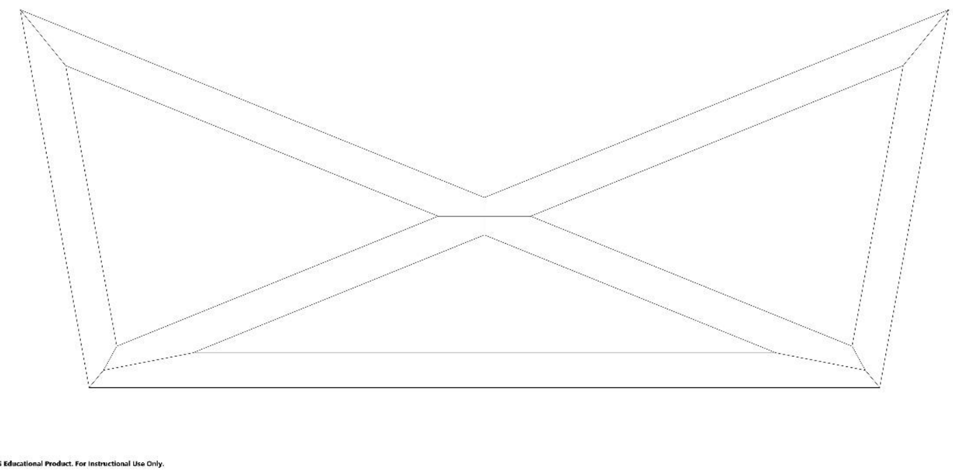
Lower Side Impact Member (Right)



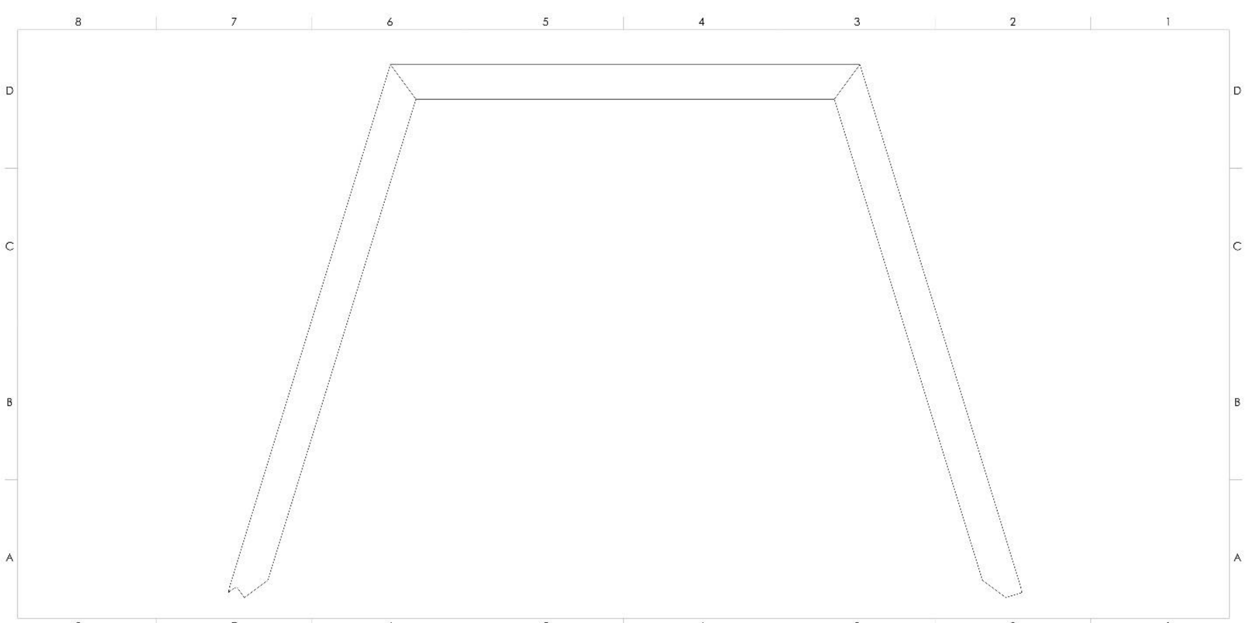
Main Roll Hoop + Upper and Lower Spar



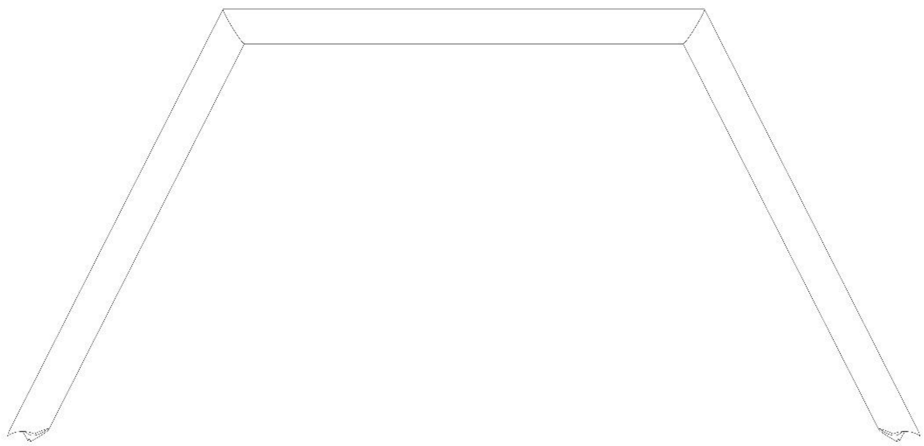
Accumulator X Brace



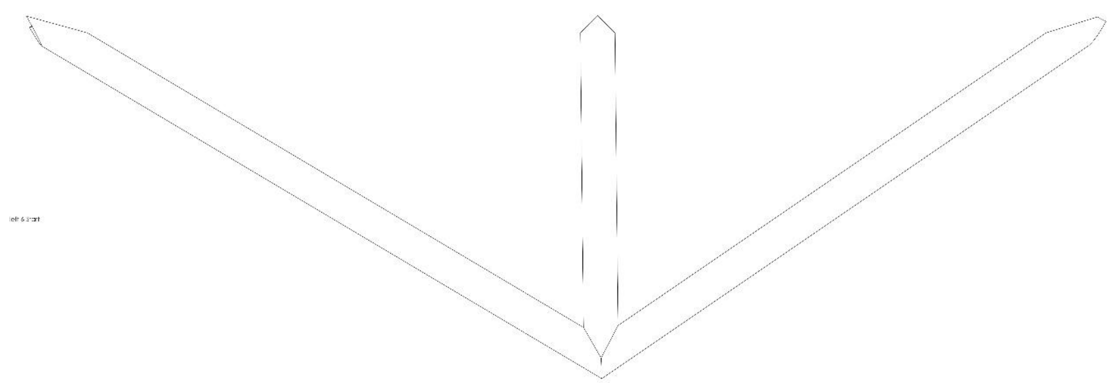
Powertrain Box Floor



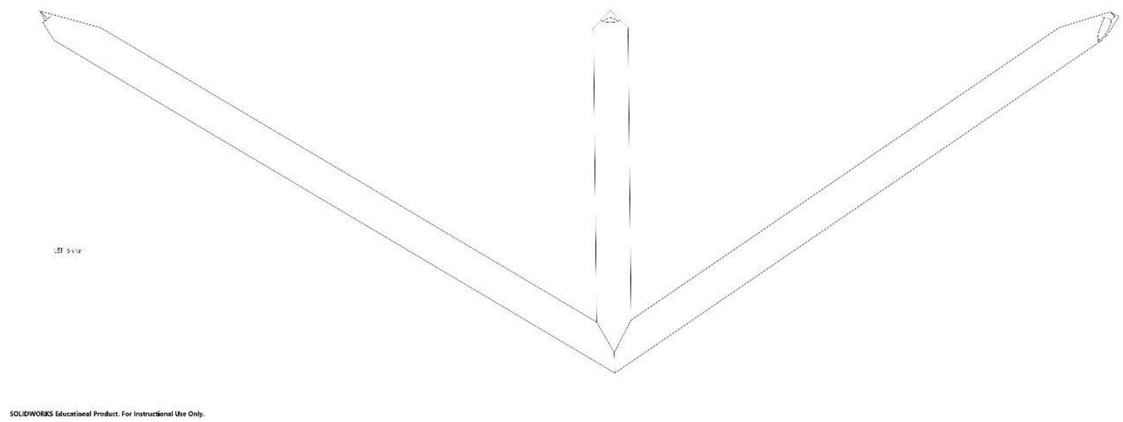
Powertrain Box Upper



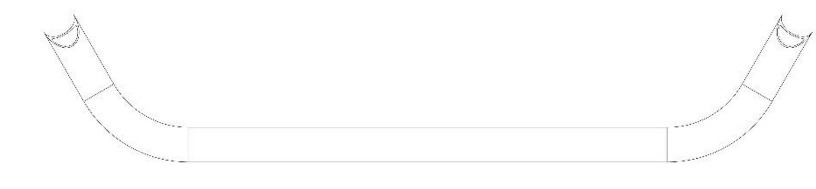
Lower 6 Star Member (Left)



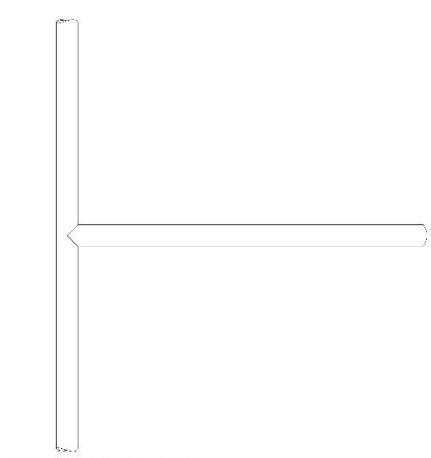
Lower Six Star Member (Right)



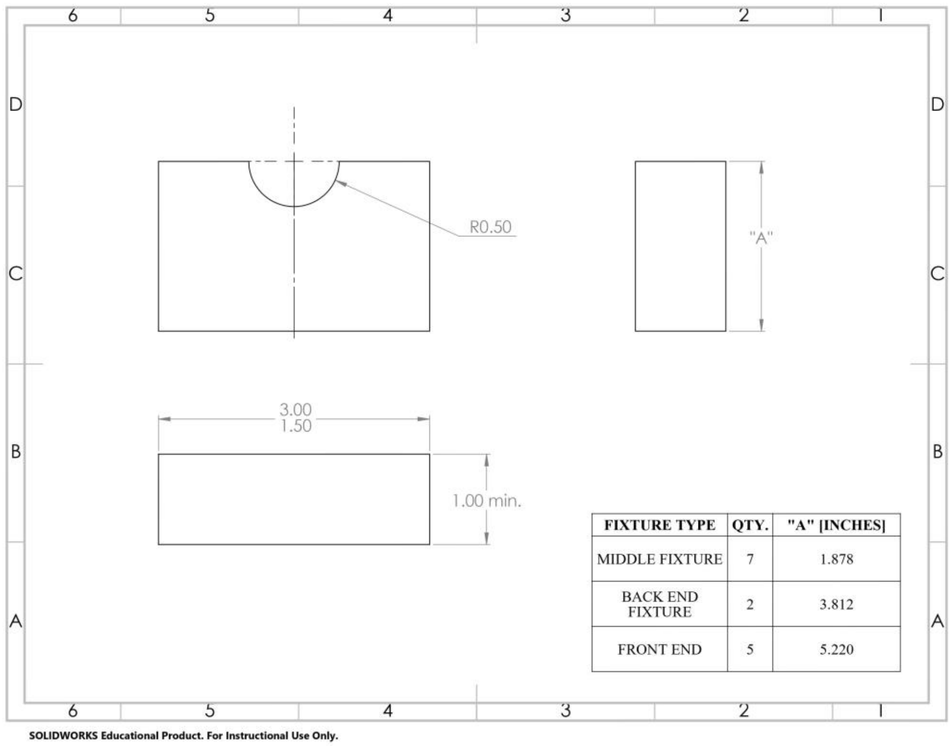
Bent Shoulder harness Bar



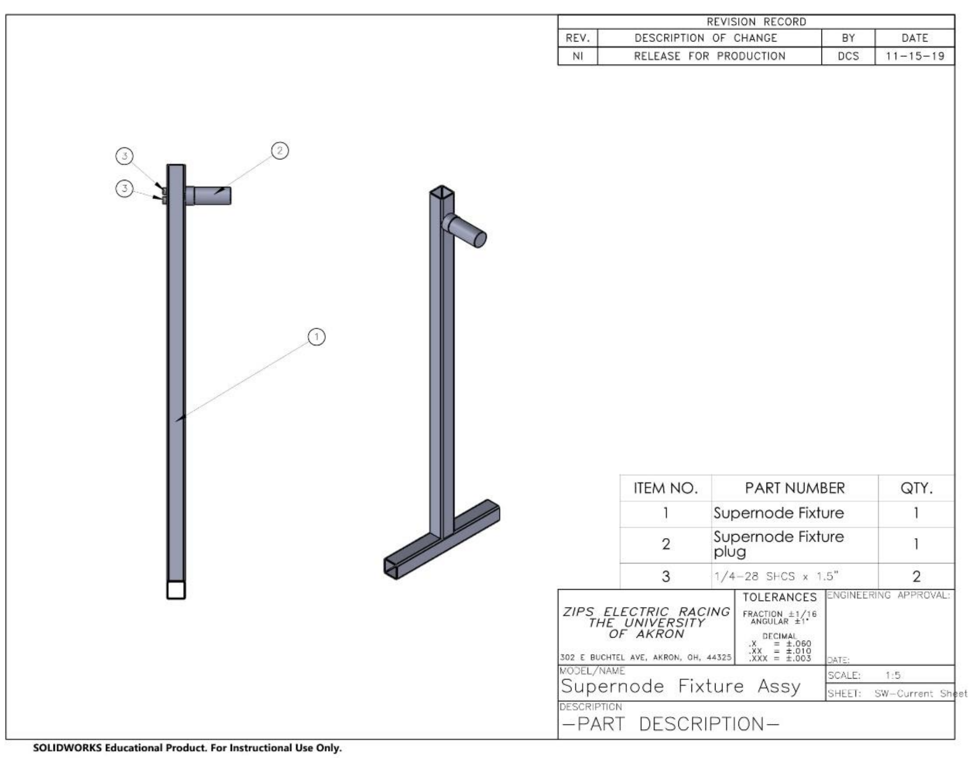
Head Restraint Support Structure



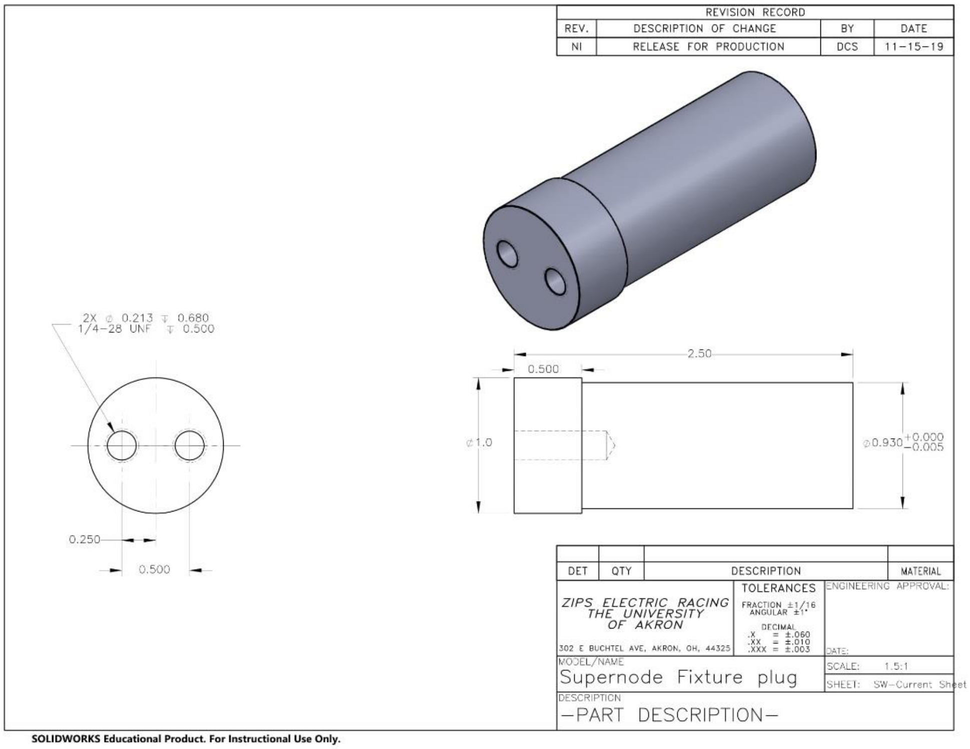
Appendix F: Fixture Drawings



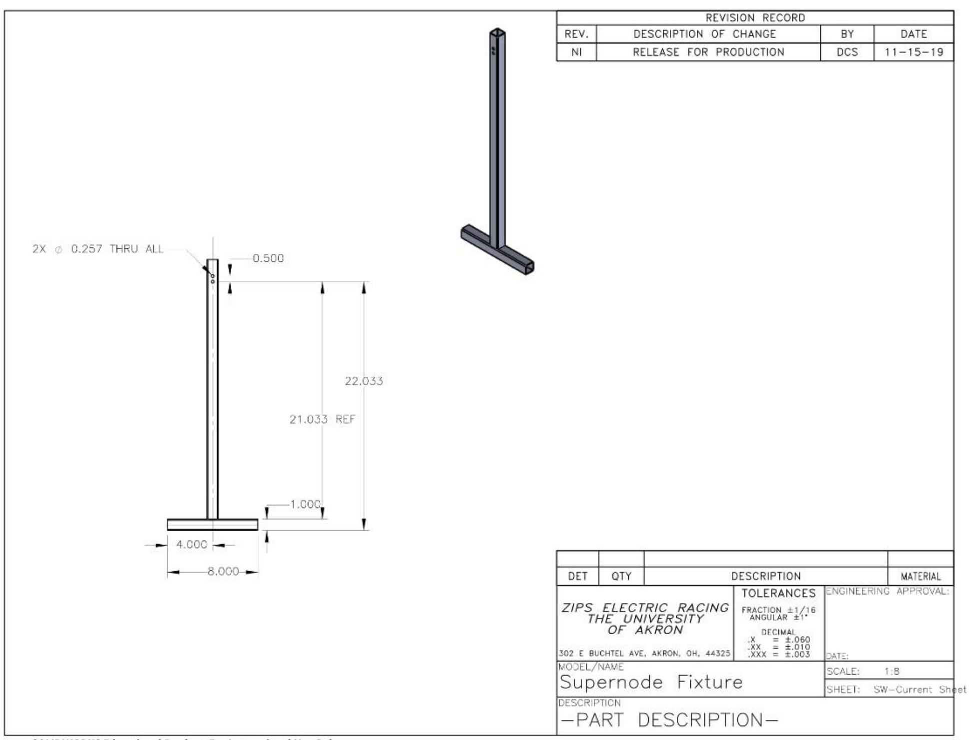
Z **Axis Fixtures**



Super node Fixture Assembly Drawing



Super node Fixture Plug Drawing



Super node Fixture Drawing

Appendix G: Frame Bill of Materials

ITEM NO.	PART NUMBER	QTY.
1	HR - 02 [.625 x .028].STEP	1
2	AB – 09 [.065].STEP	1
3	PB – 12 [.049].STEP	1
4	FS – 06 [.049].STEP	1
5	AB – 10 [.065].STEP	1
6	MRHB – 03 [.049].STEP	1
7	PB – 08 [.049].STEP	1
8	FBH – 04 [.065].STEP	1
9	SIS – 03 [.065].STEP	1
10	FS – 08 [.049].STEP	1
11	FRH – 01 [.095].STEP	1
12	PB – 04 [.049].STEP	1
13	FBH – 02 [.065].STEP	1
14	AB – 01 [.049].STEP	1
15	FS – 10 [.049].STEP	1
16	FS – 03 [.049].STEP	1
17	FBH – 03 [.065].STEP	1
18	FS – 05 [.049].STEP	1
19	PB – 06 [.049].STEP	1
20	AB – 02 [.065].STEP	1
21	SIS – 10 [.065].STEP	1
22	PB – 09 [.049].STEP	1
23	SIS – 04 [.065].STEP	1
24	FF – 04 [.049].STEP	1
25	FS – 11 [.049].STEP	1
26	PB – 05 [.049].STEP	1
27	FS – 09 [.049].STEP	1
28	SIS – 11 [.065].STEP	1
29	MRH – 03 [.049].STEP	1
30	MRHB – 05 [.049].STEP	1
31	FS – 01 [.049].STEP	1
32	AB – 11 [.065].STEP	1
33	FS – 12 [.049].STEP	1
34	SIS – 09 [.065].STEP	1
35	MRHB – 10 [.049].STEP	1
36	MRHB – 09 [.049].STEP	1
37	SC – 01 [.625 x .028].STEP	1
38	HR – 01 [.625 x .028].STEP	1
39	FS – 02 [.049].STEP	1
40	MRH – 02 [.049].STEP	1
41	AB – 06 [.049].STEP	1
42	AB – 03 [.065].STEP	1
43	MRHB – 01 [.035].STEP	1
44	SIS – 01 [.065].STEP	1
45	FBH – 01 [.065].STEP	1

46	PB – 07 [.049].STEP	1
47	HB – 01 [.095].STEP	1
48	PB – 11 [.049].STEP	1
49	SIS – 05 [.065].STEP	1
50	FF – 03 [.049].STEP	1
51	FBHS – 02 [.065].STEP	1
52	FBHS – 01 [.065].STEP	1
53	MRHB – 02 [.035].STEP	1
54	SIS – 02 [.065].STEP	1
55	FF – 01 [.049].STEP	1
56	FBHS – 03 [.065].STEP	1
57	FF – 02 [.049].STEP	1
58	SC – 02 [.625 x .028].STEP	1
59	MRH – 01 [.095].STEP	1
60	FS – 04 [.049].STEP	1
61	PB – 10 [.049].STEP	1
62	MRHB – 07 [.065].STEP	1
63	AB – 08 [.065].STEP	1
64	AB – 05 [.049].STEP	1
65	SIS – 13 [.065].STEP	1
66	HB – 03 [.049].STEP	1
67	MRHB – 04 [.049].STEP	1
68	FF – 05 [.049].STEP	1
69	MRHB – 06 [.049].STEP	1
70	FS – 07 [.049].STEP	1
71	SIS – 07 [.065].STEP	1
72	SIS – 12 [.065].STEP	1
73	PB – 13 [.049].STEP	1
74	AB – 12 [.065].STEP	1
75	PB – 03 [.049].STEP	1
76	AB – 04 [.049].STEP	1
77	PB – 02 [.049].STEP	1
78	HB – 02 [.049].STEP	1
79	MRHB – 08 [.065].STEP	1
80	SIS – 06 [.065].STEP	1
81	PB – 01 [.049].STEP	1
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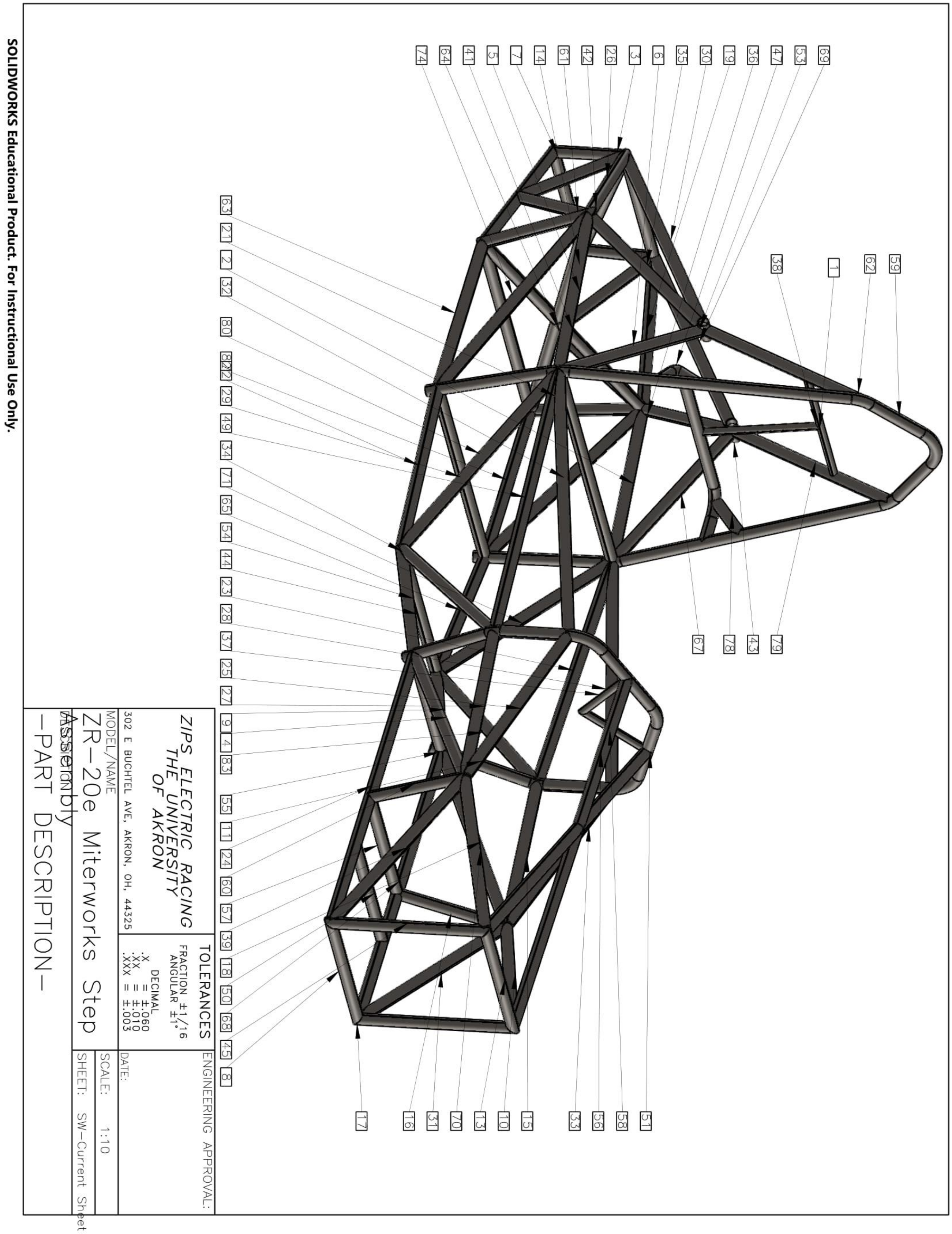
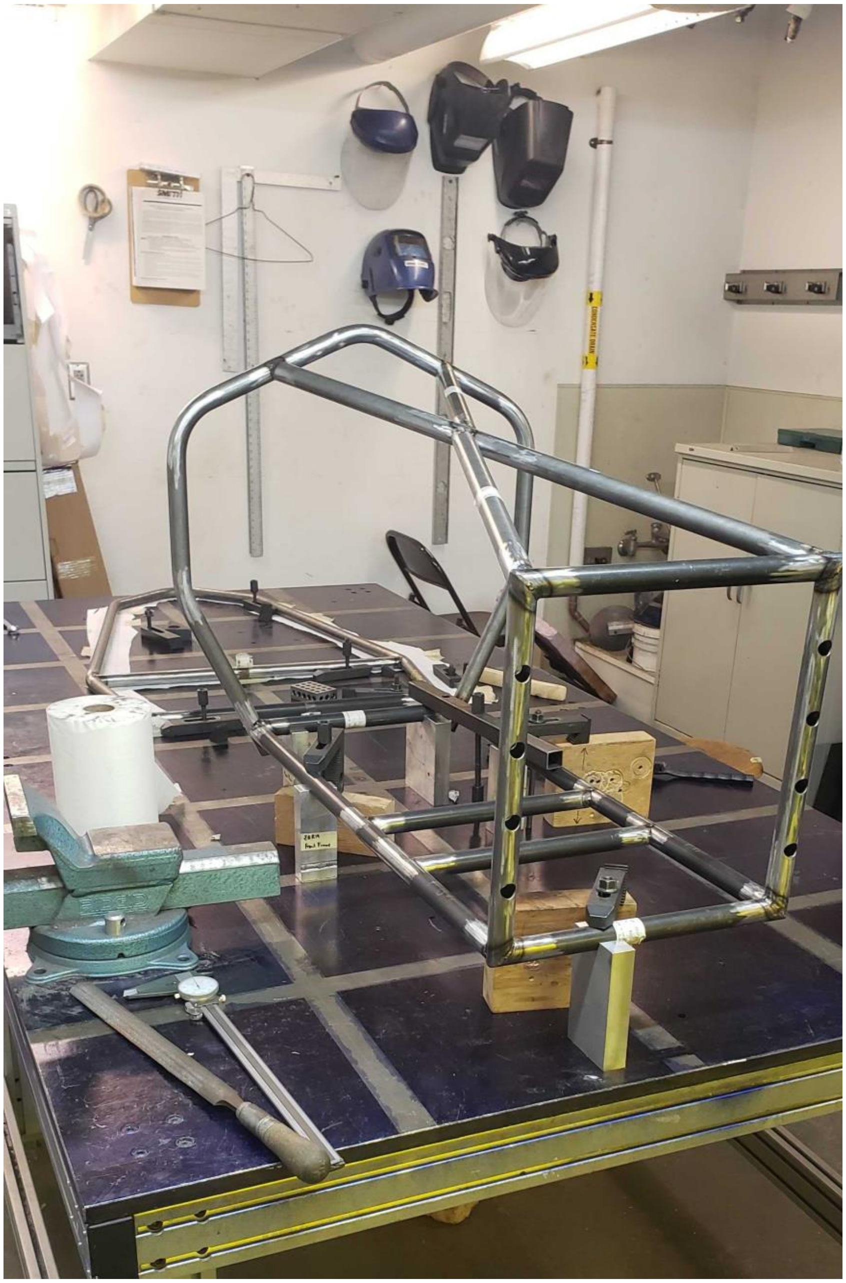
83	SIS – 08 [.065].STEP	1


SOLIDWORKS Educational Product. For Instructional Use Only.
ZIPS ELECTRIC RACING
THE UNIVERSITY OF AKRON
302 E BUCHTEL AVE, AKRON, OH, 44325
MODEL/NAME
ZR-20e Miterworks Step Assembly
-PART DESCRIPTION-
TOLERANCES
FRACTION ±1/16
ANGULAR ±1°
DECIMAL
.X = ±.060
.XX = ±.010
.XXX = ±.003
ENGINEERING APPROVAL:
DATE:
SCALE: 1:10
SHEET: SW-Current Sheet

Appendix H: Pictures of Frame during Manufacturing



Welded Front Box Structure and Main Roll Hoop on 1:1 Template

Rear of Frame after welding in Super node and Main Hoop Braces and Supports

Complete Painted Frame with Aircraft Fabric Coating

8 References

Gross, Richard J. Vehicle Dynamics. Chapter 10: Frame Characteristics. 2015.

SAE International. (2020). *Formula SAE Rules 2020* (Version 2.2 ed.) FSAEonline. Retrevied from fsaeonline.com/cdsweb/gen/DocumentResources.aspx

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