

## Appendix G. Mechanical VDR Form



# ASC2018 Mechanical VDR Form

School/Team: University of Waterloo / Midnight Sun Solar Car Team Entry # 24

## Mechanical VDR/Table of Contents

|     |  |            |
|-----|--|------------|
| 1.  | History of team and vehicle (one paragraph)  | page _____ |
| 2.  | <b>Type of vehicle:</b> Single-Occupant ( <u>  </u> ), Multi-Occupant ( <u>x</u> ) check one   |            |
| 3.  | Vehicle weight (estimate) ( <u>440</u> ); Units ( <u>  </u> ) kg ( <u>  </u> ) lbs,  |            |
| 4.  | Vehicle weight distribution (estimate), front ( <u>215</u> ), rear ( <u>225</u> ), lbs/kg.   |            |
| 5.  | Vehicle description shall be presented by profile and top view drawings showing the placement of major components such as driver, battery, ballast box, crush zone, seat belts mounting points, etc, along with overall dimensions including wheel base and tread  | page _____ |
| 6.  | <b>Frame/chassis and roll cage type:</b> tubular frame ( <u>x</u> ), composite ( <u>  </u> ), check one.<br>Drawing shall show the (1) occupants positioned in the frame/chassis, (2) material specs of all metal components, and (3) compliance with Reg 10.3   | page _____ |
| 7.  | <b>Roll cage:</b> Profile and frontal drawings shall include material specs and show compliance with Regs 10.3,10.3.B,10.3.C,10.3.G  | page _____ |
| 8.  | <b>Seat Belts:</b> 5 point ( <u>x</u> ), 6 point ( <u>  </u> ), check one<br>Drawing shall indicate location of mounting points and compliance with Reg. 10.3.E  | page _____ |
| 9.  | <b>Braking system:</b> Front wheel only ( <u>x</u> ), Front-rear ( <u>  </u> ), check one.<br>Schematic and description of primary braking system shall include parking brake and component specs demonstrating compliance with Regs.10.5 and 10.6   | page _____ |
| 10. | <b>Steering system type:</b> rack and pinion ( <u>x</u> ), other ( <u>  </u> ), check one.<br>Description shall include component selection and specs  | page _____ |
| 11. | <b>Steering stops:</b> Description/drawing/photos shall show compliance with Reg 10.7.B.   | page _____ |
| 12. | <b>Front suspension:</b> type: a-arm ( <u>x</u> ), other ( <u>  </u> ), check one<br>Description shall include drawing/photos, component specs, and engineering analysis demonstrating proper selection and sizing of rod ends with shear loads under applied loads as specified in Appendix F, section F.2            | page _____ |
| 13. | <b>Rear Suspension:</b> type: a-arm ( <u>  </u> ), swing arm ( <u>x</u> ), other, check one.<br>Description shall include drawing/photos, component specs, and engineering analysis demonstrating proper selection and sizing of rod ends with shear loads under applied loads as specified in Appendix F, section F.2 | page _____ |
| 14. | <b>Tires and rims:</b> Description shall include brand, load, speed, and pressure rating to comply with Regs. 10.2   | page _____ |
| 15. | <b>Hub design:</b> Drawings showing wheel-hub assembly   | page _____ |
| 16. | <b>Crush zone:</b> type: foam ( <u>x</u> ); tubular ( <u>  </u> ),check one<br>Description/drawing shall support compliance with Reg. 10.3.F   | page _____ |
| 17. | <b>Battery box:</b> Description/drawing to show how battery box is constructed and secured in the chassis as per Reg. 8.4.B  | page _____ |
| 18. | Description/drawing to show independent methods of array attachment as per Reg. 10.1.C   | page _____ |
| 19. | <b>Fasteners:</b> Description of compliance with Reg. 10.4   | page _____ |

20. **Vehicle Impact Analysis:** Method: Classical (  ), FEA (x), Testing (  )  
Analysis shall be performed as per Appendix F Section F.3 and the results shall be  
presented in terms of factor of safety in tabulated form

page \_\_\_\_\_

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Mechanical contact: Name: Devon Copeland  
Email address: devon.copeland@uwmidsun.com

Phone: 226-792-7383

Project Manager: Name: Tak Alguire  
Email address: tak.alguire@uwmidsun.com



Midnight Sun Solar Car Team  
University of Waterloo

MSXII  
**Vehicle Design Report**  
Mechanical

Prepared by:  
Minghao Ji  
[minghao.ji@uwmidsun.com](mailto:minghao.ji@uwmidsun.com)  
November 16, 2017

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## 1 History

Midnight Sun was founded in 1988 at the University of Waterloo. The team has produced 11 solar-powered vehicles since its inception, numbered MSI through MSXI. MSX and its predecessors have been traditional Challenger class cars. MSXI was the team's first attempt at a Cruiser class vehicle, which ultimately suffered from design issues relating to its monocoque design. With MSXII, the team has regrouped and designed a new Cruiser vehicle from the ground up, focussing strongly on reliability, safety, and manufacturability.

## 2 Contacts

Questions regarding the mechanical design and implementation of MSXII should be directed to one of the following contacts:

| Name           | Title               | Phone        | Email                       |
|----------------|---------------------|--------------|-----------------------------|
| Tak Alguire    | Project Manager     | 519-574-4610 | tak.alguire@uwmidsun.com    |
| Minghao Ji     | Engineering Manager | 519-500-1292 | minghao.ji@uwmidsun.com     |
| Devon Copeland | Mechanical Lead     | 226-792-7383 | devon.copeland@uwmidsun.com |

## 3 Overview

MSXII is a dual-occupant Cruiser class vehicle. Its structural design uses a steel alloy tube chassis with non-structural fibreglass body panels. The majority of the vehicle's powertrain systems are located behind the occupant cell, including the battery pack, power junction box, motor controllers, and EV charger. The vehicle is rear-wheel driven by two hub-mounted DC motors. The locations of these components are marked in Figure 1 and Figure 2. Major vehicle dimensions are summarized in Table 1.

## 4 Chassis

### 4.1 Design

The chassis is a tube structure enclosing the occupant cell with small front and rear subframes to support suspension hardpoints. Smaller non-structural tube members will extend from the main frame to provide support to body panels as necessary. The majority of tubes are round, with square tubes being used only for elements intended to mount suspension and powertrain components (battery pack, motor controllers). Chassis elements

|            |        |
|------------|--------|
| Wheelbase  | 2.60 m |
| Track      | 1.60 m |
| Max length | 4.68 m |
| Max width  | 2.02 m |
| Max height | 1.23 m |

Table 1: Table of major vehicle dimensions

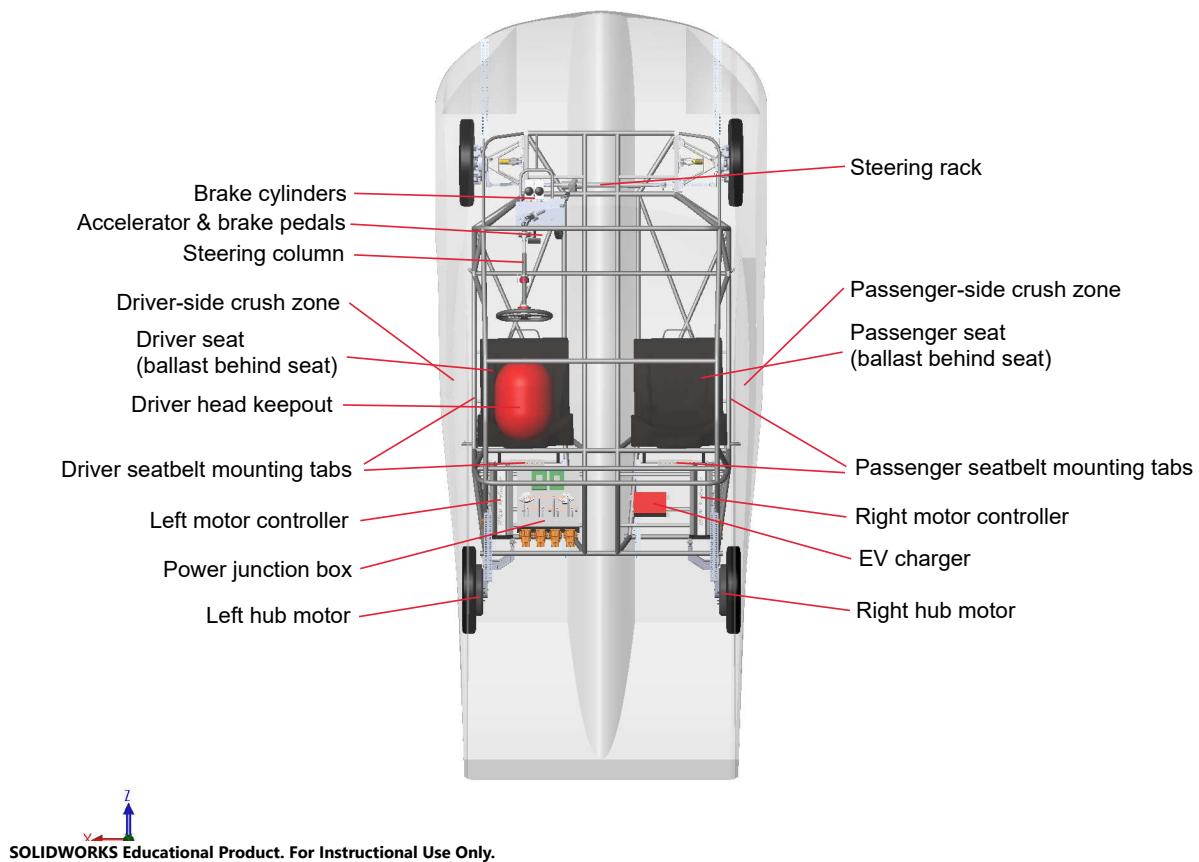


Figure 1: Top view showing major dimensions and system positions

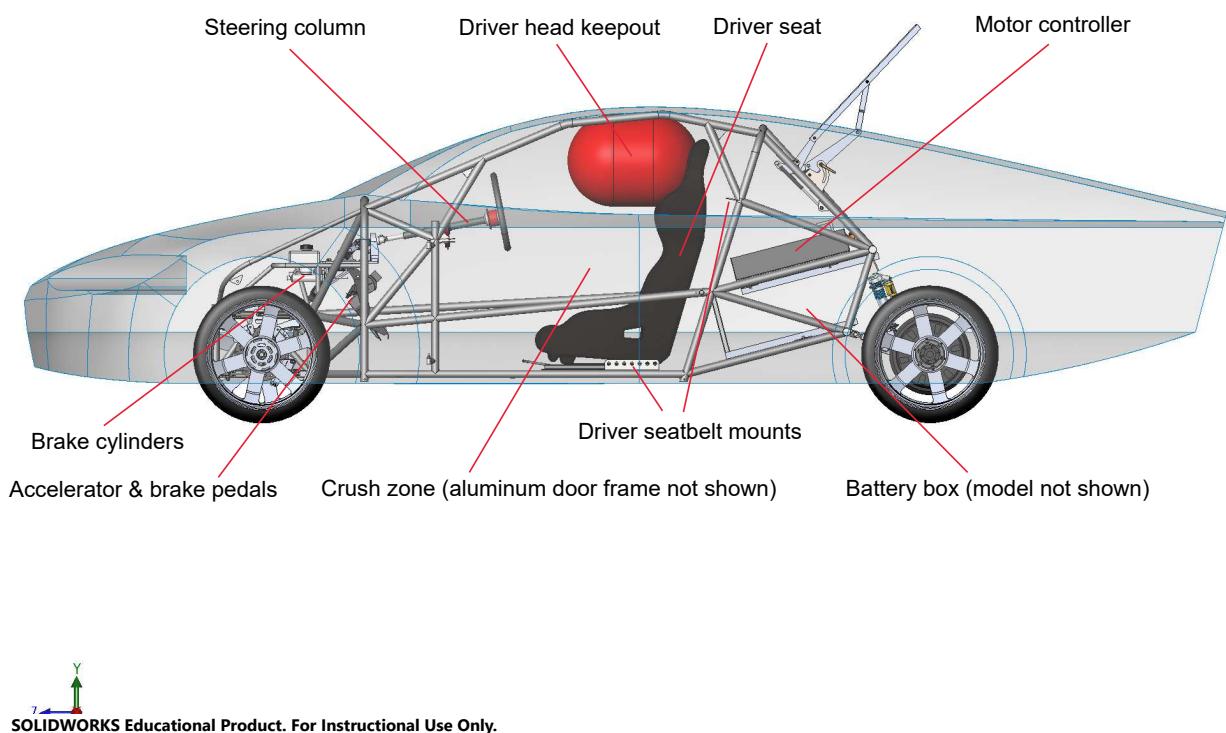


Figure 2: Side view showing major dimensions and system positions

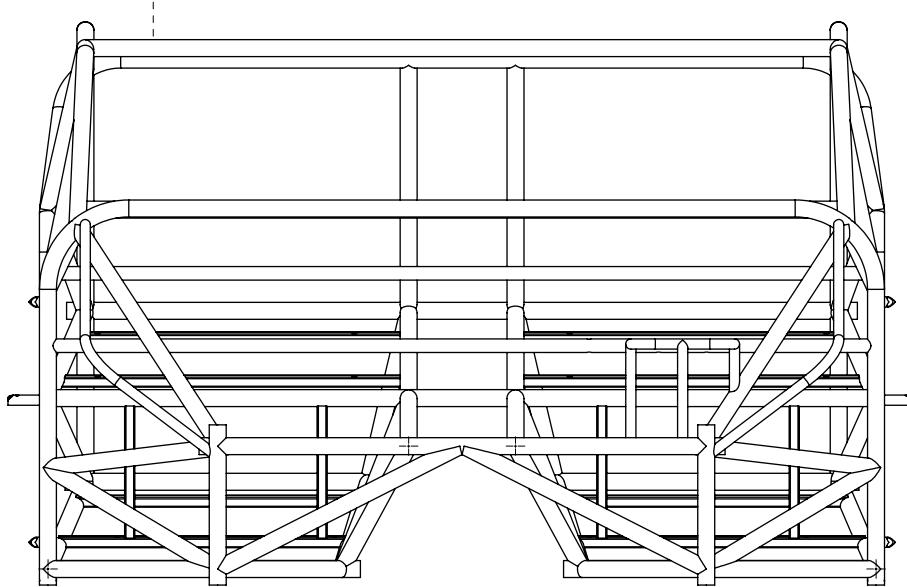


Figure 3: Chassis, front view

use SAE 4130N chromoly tubes with diameters or side lengths ranging from 0.750" to 1.250", and wall thicknesses ranging from 0.035" to 0.065". Isometric drawings of the chassis are shown in Figures 3, 4, and 5.

## 4.2 Manufacturing

Bending, cutting, and profiling of tubes was done by an external supplier. Welding of the chassis was done by a professional welder using GTAW, with support from team members for jigging and assembly. A complete welding jig was designed in CAD and manufactured using 80/20 aluminum extrusion tubing, shown in Figure 6. Custom tube clamps were machined by the team to slot into jig members and fully support all chassis elements through multiple stages of assembly and welding.

## 4.3 Roll cage

The roll cage is integrated into the design of the chassis members enclosing the occupant cell. For the purposes of ASC regulations, the roll cage can be considered to include the A and B pillar hoops and elements connecting these two hoops lengthwise through the car. For clarity, these elements have been highlighted in Figure 7.

## 4.4 Doors

The vehicle's doors are designed with an aluminium planar tube structure enclosed by composite panels. Protection against side impacts is improved by the addition of 4 inches (approx. 10 cm) of energy absorbing foam (Impaxx™ 700 Series from DOW Chemical). This foam, combined with the aluminum frame and composite outer panel, together are designed to satisfy crush zone requirements for ASC. The total thickness of the door (outer face to chassis) is 15 cm. The aluminum frame is designed to brace against chassis members in the event of a side impact and meets the same 5G requirement as the chassis, so that the foam layer can crush and absorb energy. FEA for the door frame is shown in Figures 37, 38, and 39 in Appendix B.

## 5 Seat belts

MSXII is equipped with 5-point seat belts for both occupants. Seat belt hardpoints are mounted to metal tabs welded to chassis members, shown in Figure 8. Figure 9 shows one of these tabs. Figures 10 and 11 demonstrate compliance with ASC regulations 10.3.E.

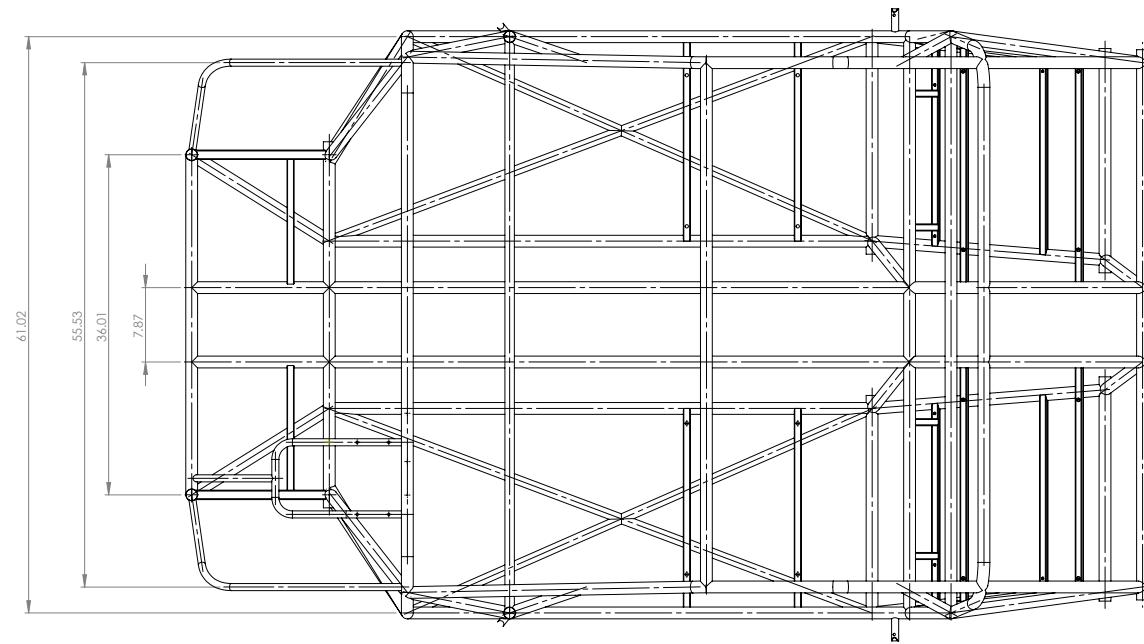


Figure 4: Chassis, top view

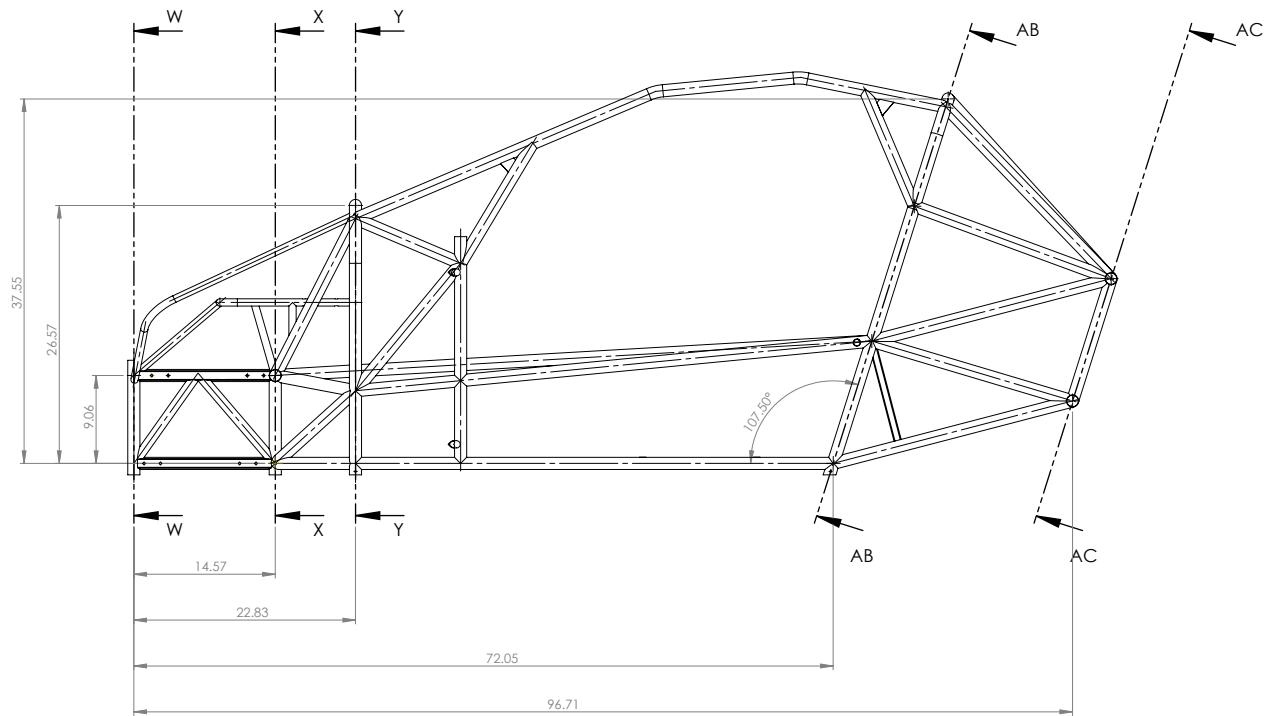
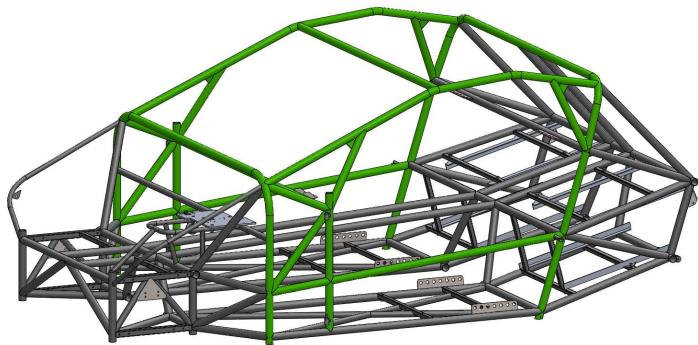


Figure 5: Chassis, side view

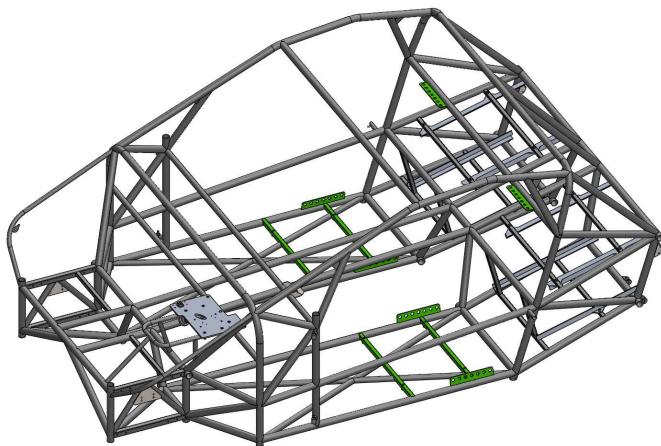


Figure 6: Welding jig on rotating mount



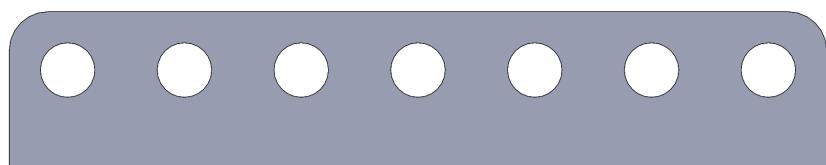
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Figure 7: Chassis with roll cage elements highlighted



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Figure 8: Chassis mounting points for seat belts



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Figure 9: Single seat belt tab

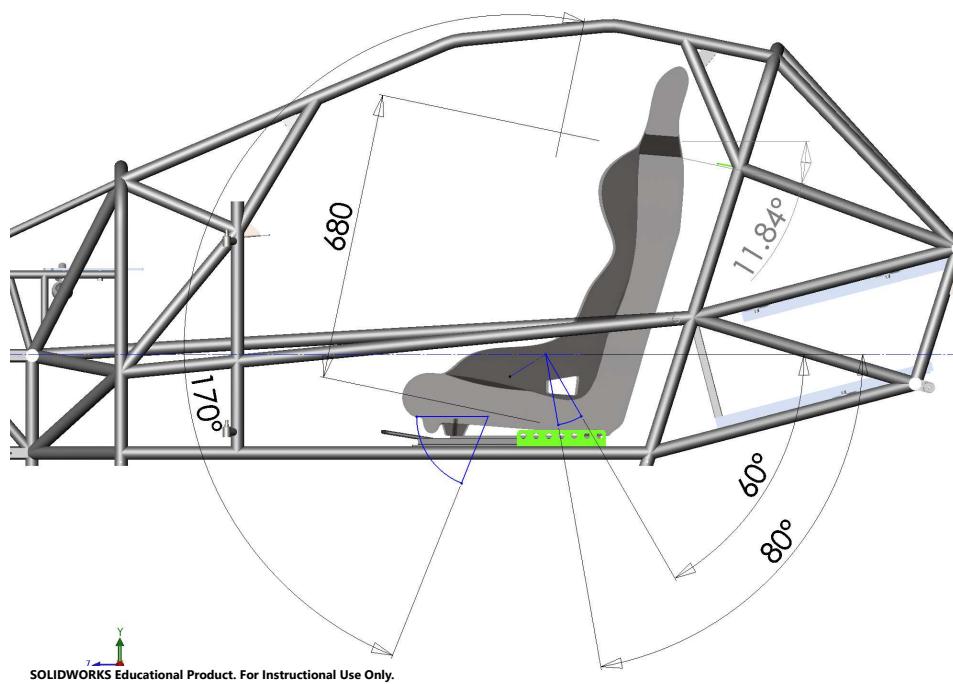


Figure 10: Side view of seat belt geometry

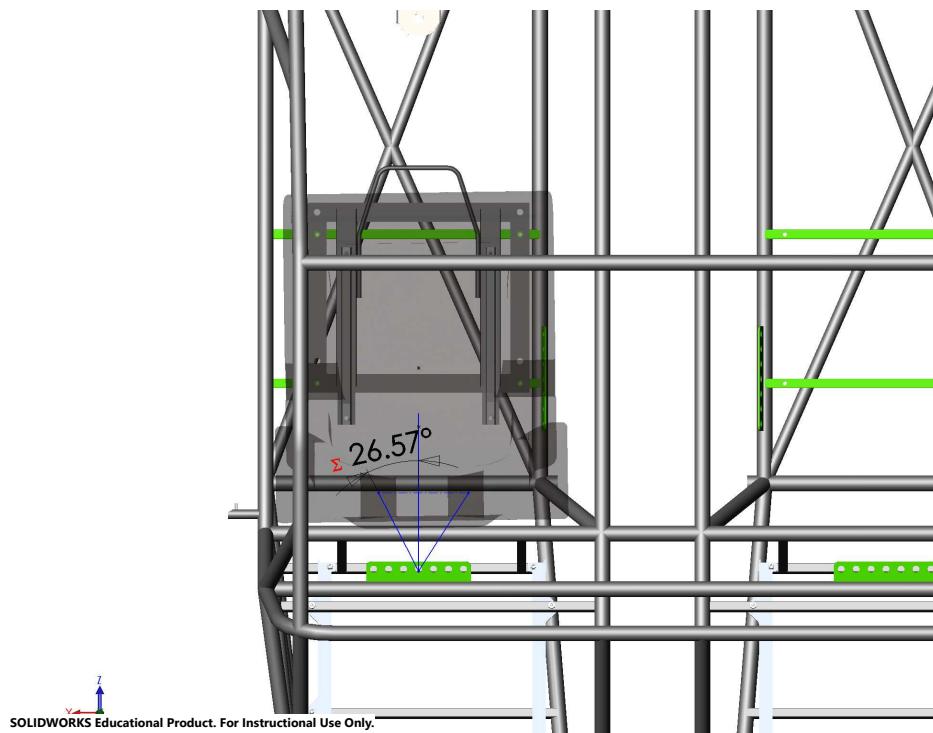


Figure 11: Top view of seat belt geometry

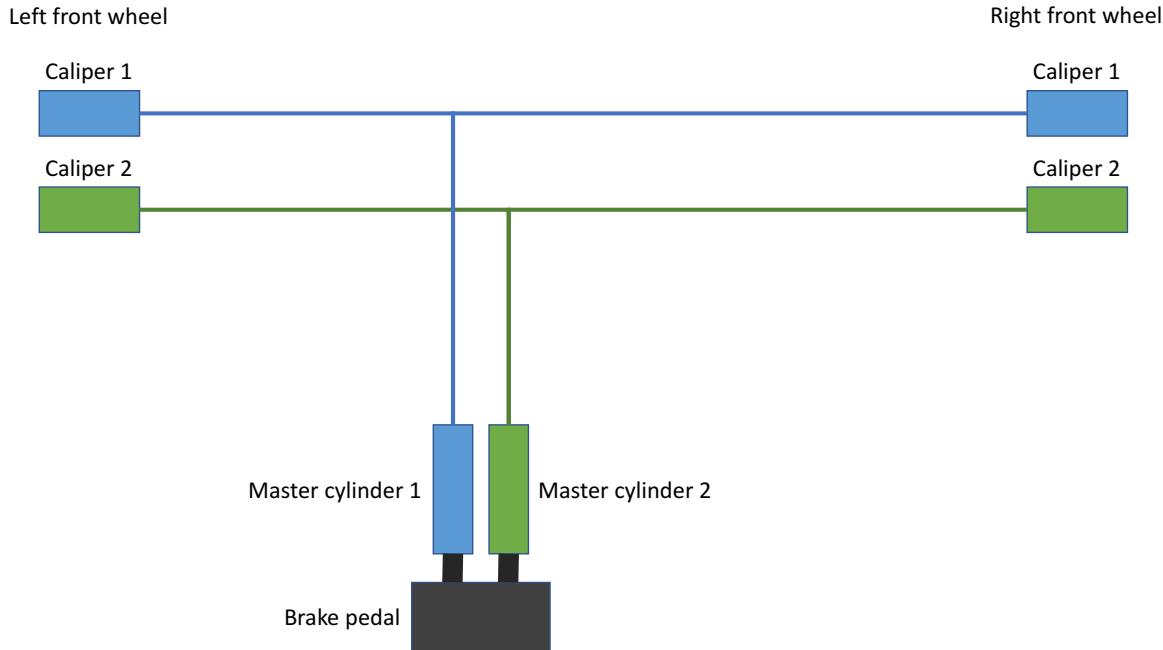


Figure 12: Schematic of primary braking system

## 6 Braking system

### 6.1 Primary brakes

The primary braking system is designed with dual redundant front braking, consisting of two identical systems with separate master cylinders, hydraulic lines, and calipers to each of the left and right wheels. The master cylinders are operated in unison via a single mechanical brake pedal. The brake pedal assembly is turnkey from Wilwood (part 340-15079) and has an integrated balance bar. A schematic of the primary system is shown in Figure 12.

Front brake calipers are Willwood parts 120-8374 (left) and 120-8373 (right). Willwood's website indicates the caliper pads have  $2 \text{ in}^2$  ( $12.9 \text{ cm}^2$ ) contact area and 0.30" (7.6 mm) depth including the backing plate.

The master cylinders are Willwood part 206-3374. They have a 3/8"-24 outlet size which will need to be connected via a suitable brake line to the M10 x 1.25 inlets of the calipers. Brake lines will be DOT-approved hose assemblies sized for 3/8"-24 on one end and M10 on the other end via a banjo joint. The brake pedal is Willwood part 340-15079 and is mounted in the standard configuration to the left of the accelerator pedal.

Brake rotors will be custom-machined to the disk thickness and diameter supported by the Willwood calipers. All mounting geometry on the suspension upright for primary calipers are designed to position the primary calipers in the optimal positions to meet braking specifications.

### 6.2 Parking brake

The parking brake will be implemented by a cable-actuated caliper mounted at one of the front wheels. The caliper is the Tolomatic ME10LA (part number 0732-0003). It will share the same brake disk as the primary braking system but is otherwise mechanically independent. Due to unresolvable dimensioning differences between the Tolomatic and Willwood calipers, the parking brake caliper cannot be mounted perfectly as per the manufacturer's recommendations and will have only 80% overlap with the brake disk. However, this is expected to provide more than sufficient countertorque to keep the vehicle stationary as per ASC regulations 10.6.

Figure 13 shows a front suspension upright with all three calipers mounted (two primary and one parking).

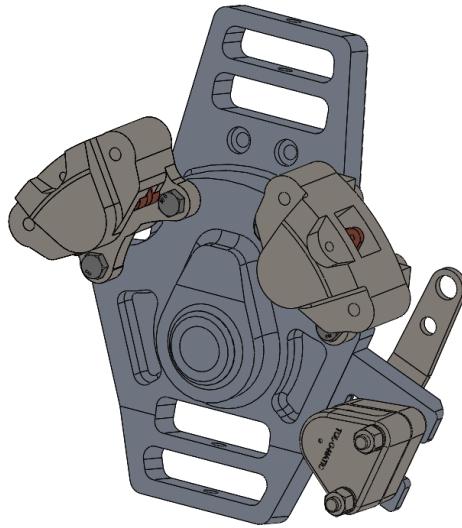


Figure 13: View of dual-primary calipers and parking caliper on front suspension upright

## 7 Steering system

The steering system uses a rear-steering, left-hand-drive rack and pinion from Helix (part number 188754). The system uses a collapsible steering column from Sweet Mfg. (part number 405-10310). The linkage uses dual U-joints to circumvent interfering brake system components and is shown in Figure 14. The travel of the steering rack is limited by a sleeve floating on the interface between the rack and the rack extensions. When at the maximum steering angle, the flange on the rack extension datums against the rack and pinion housing via the sleeve.

## 8 Suspension

### 8.1 Front suspension

The front suspension uses dual A-arms with an outboard damper and coilover spring. The upper and lower control arms are custom-built from 4130 chromoly tubes. The damper and coilover are a single integrated assembly supplied by Öhlins, sold as the TTX25, which is marketed for Formula SAE vehicles. Figure 15 shows the front suspension assembly.

The front suspension lower control arm bears the majority of the shear stress from road forces. Both the upper and lower control arms use 7/16" spherical bearings (QA1 part number YPB7T), which are pressed into their respective chromoly bearing seats in the control arms. Under maximum loading conditions, the stress due to bending in the bolt held in double shear was found to be 204.63 MPa. Using an SAE grade 5 results in a safety factor of approximately 3.0.

Since the lower bearing will be carrying approximately 25% of the weight of the car, a load bearing flange has been added on the top side of the bearing seat which constrains it axially whenever in compression. A CAD nominal 12  $\mu\text{m}$  diametral press fit retains the spherical bearing in rare cases where the suspension rebound is sufficient to reverse the load. As an added precaution, a set screw in both the top and bottom helps to retain the bearing.

### 8.2 Rear suspension

The rear suspension uses independent trailing arms mounted outwards from the rear of the chassis. The trailing arm itself is custom-machined and mounts the same Öhlins TTX25 shock absorber as the front suspension. Figure 18 shows the rear suspension assembly.

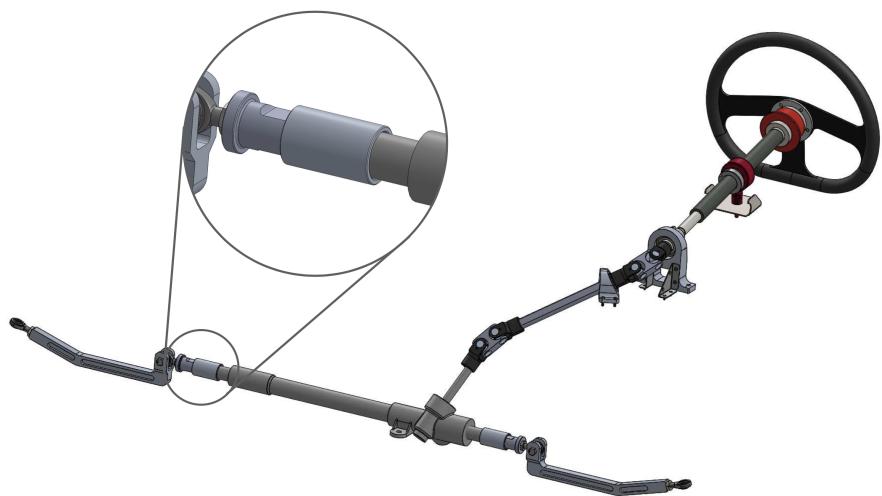
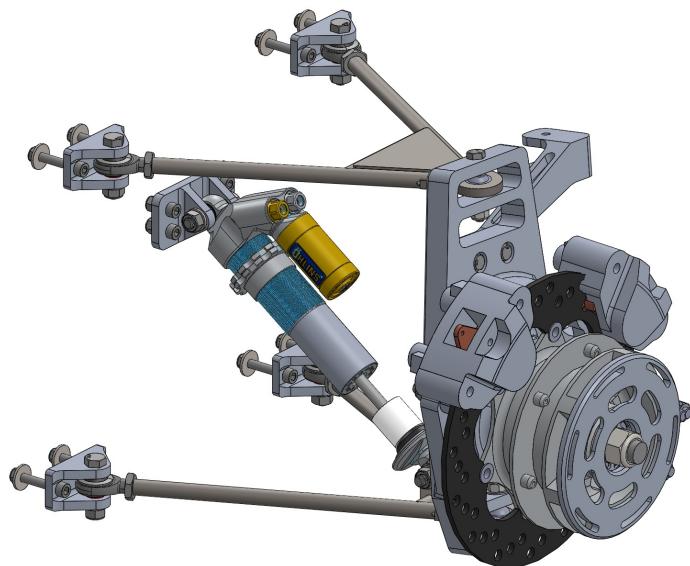


Figure 14: View of steering assembly, hardstop shown enlarged



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Figure 15: View of front suspension assembly (parking brake caliper obstructed by hub)

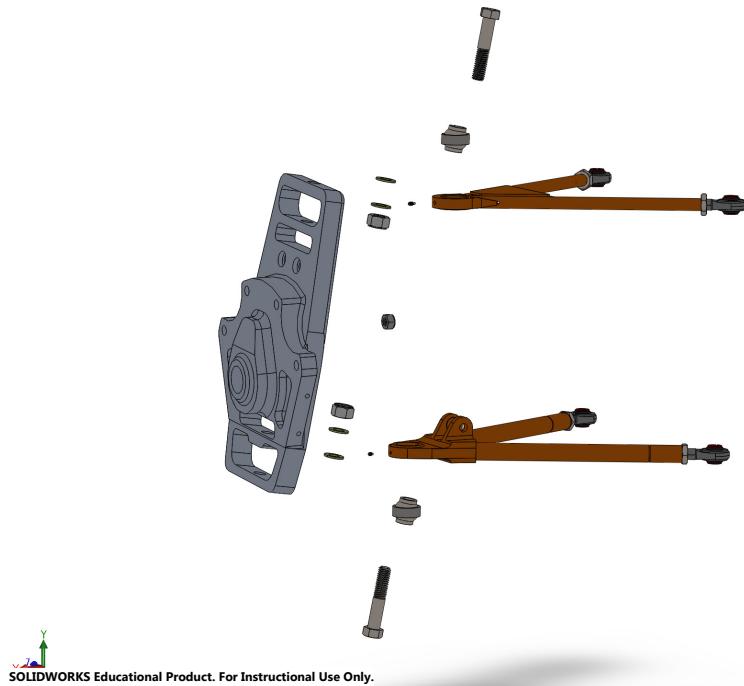


Figure 16: View of front suspension assembly, exploded

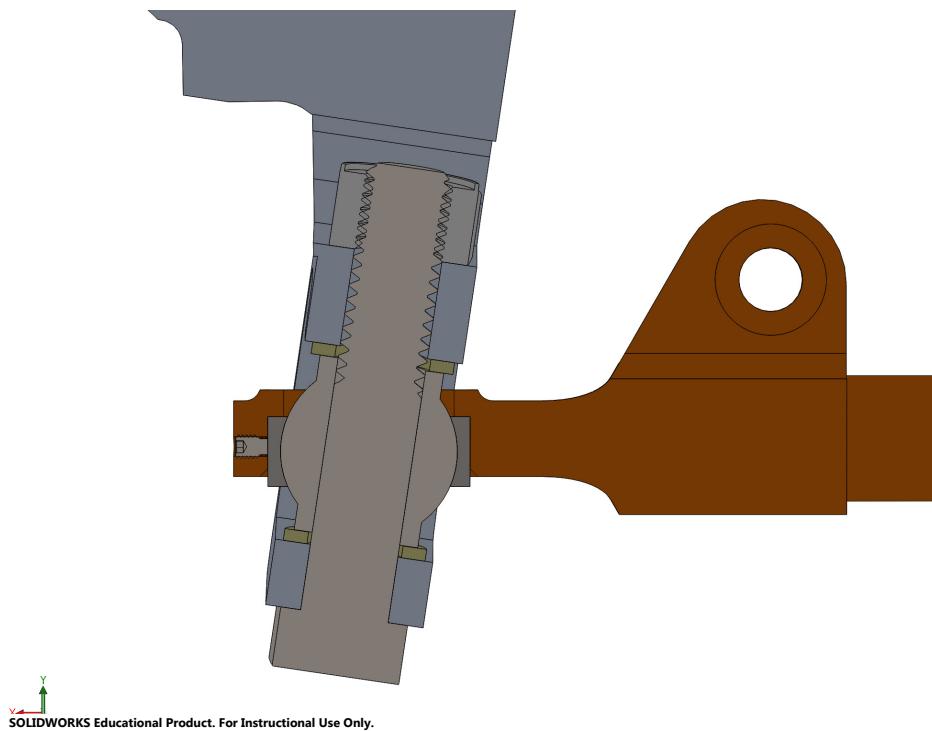


Figure 17: View of front suspension critical rod end, cross-section

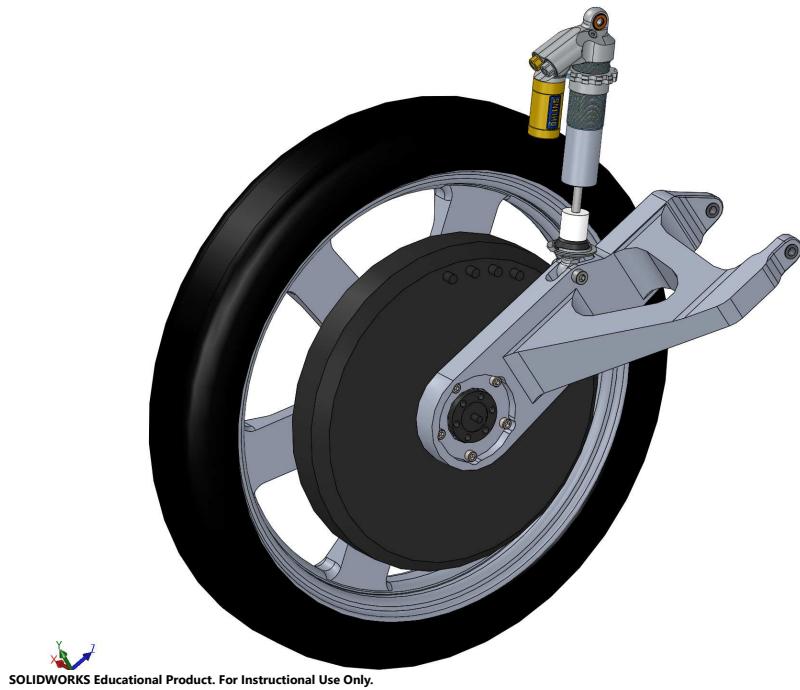


Figure 18: View of rear suspension assembly

The rear suspension pivots about plain bearings pressed into the trailing arm (QA1 part number 39N443). Stress in the trailing arm at the plain bearings was simulated using FEA as shown Figure 18 to verify sufficient safety factor. The lack of rod ends allows a smaller interface with the rear suspension clevis mounts, which would otherwise need to be sized significantly larger.

## 9 Finite element analysis

Finite element analysis was performed using ANSYS on the chassis and all suspension and steering components (downstream from the rack and pinion). FEA of the chassis and door followed the specifications provided by the ASC regulations. A general methodology was to fix a solid beam or wall in space, and apply a 5G acceleration to the chassis against it. Images for FEA simulations of each requested scenario are shown in Appendix B.

Worst-case loading forces on each wheel were used to derive appropriate constraints and forces for FEA simulation of the suspension and steering system. A complete derivation and summary of loading forces on each wheel is given in Appendix A. Images of all FEA simulations for suspension and steering are available in Appendix C.

### 9.1 Front suspension

#### 9.1.1 Clevises

Hand calculations were used to resolve the forces from the road as loading onto the clevises. The back face of the clevis was constrained with compression only support. Cylindrical supports were used for the bolt holes and fastener pretension was added. Frictional contacts were added between the fasteners and the clevis.

#### 9.1.2 Upper control arms

Contacts were modeled between the control arm tubes and the bearing plate. Forces were applied to the bearing plate based on hand calculations.

### 9.1.3 Lower control arms

Contacts were modeled between the control arm tubes and the mounting tabs on the coilover clevis. Forces were applied to the profile that the bearing sits in, based off of hand calculations.

### 9.1.4 Uprights

A dummy wheel was modeled to which forces were applied. The dummy wheel contacted the spindle with a frictional contact which then applied a load to the upright. The brake forces were applied to the caliper mounting holes, assuming only one caliper was providing all braking force.

### 9.1.5 Spindles

A dummy wheel was modeled to which forces were applied. The dummy wheel contacted the spindle with a frictional contact which then applied a load to the upright.

### 9.1.6 Upper bearing plates

Contacts were modeled between the control arm tubes and the bearing plate. Forces were applied to the bearing plate based on hand calculations.

### 9.1.7 Coilover control arm tabs

The maximum force on the front wheel was resolved as a compressive load in the coilover and applied to this tab.

### 9.1.8 Coilover mounting plates

Hand calculations were used to resolve the forces from the road as loading onto the clevises. For this simulation a frictional contact was added between the clevis and the mounting plate. Dummy chassis tubes were modeled behind the mounting plate and welded edges were fixed.

## 9.2 Rear suspension

### 9.2.1 Clevises

The worst case of four loading scenarios was taken (2 clevis positions, each with either the inside or outside wheel when rounding a corner). It was assumed that all lateral force was applied to a single clevis because otherwise this is a statically indeterminate problem on paper.

### 9.2.2 Coilover tabs

The maximum normal force and acceleration force on the rear wheel was resolved as a compressive load in the coilover and applied to this tab.

### 9.2.3 Trailing arms

Similar to the front suspension, the trailing arm was simulated using a dummy wheel model. A force was applied to the contact patch and supports were added to the rod end, plain bearing and coilover clevis on the trailing arm.

## 9.3 Steering

### 9.3.1 Steering arms

A compression support was added on the face datuming off of the upright. The maximum lateral force on the tire during 1G cornering was resolved as a torque on the upright. This torque was applied by a bearing load acting at the end of the steering arm.

| Part Number | Part Name                    | Material             | Max Stress (MPa) | Safety Factor |
|-------------|------------------------------|----------------------|------------------|---------------|
| MS00015     | Coilover Clevis              | Aluminum, 7075       | 147              | 3.4           |
| MS00029     | Upper Control Arm Clevis     | Aluminum, 7075       | 191              | 2.6           |
| MS00102     | Lower Control Arm Clevis     | Aluminum, 7075       | 198              | 2.5           |
| MS00017     | Upper Control Arm            | Chromoly Steel, 4130 | 199              | 2.3           |
| MS00018     | Lower Control Arm            | Chromoly Steel, 4130 | 226              | 2.0           |
| MS00019     | Upright                      | Aluminum, 7075       | 210              | 2.4           |
| MS00020     | Spindle                      | Chromoly Steel, 4140 | 177              | 2.3           |
| MS00030     | Upper Bearing Plate          | Chromoly Steel, 4130 | 141              | 3.3           |
| MS00036     | Coilover Control Arm Tab     | Chromoly Steel, 4130 | 159              | 2.9           |
| MS00038     | Coilover Mounting Plate      | Chromoly Steel, 4130 | 147              | 3.1           |
| MS00086     | Rear Suspension Clevis Mount | Chromoly Steel, 4130 | 231              | 2.0           |
| MS00047     | Rear Suspension Coilover Tab | Chromoly Steel, 4130 | 147              | 3.1           |
| MS00065     | Trailing Arm                 | Aluminum, 7075       | 263              | 1.9           |
| MS00074     | Steering Arm                 | Aluminum, 6061-T6    | 77               | 3.5           |
| MS00101     | Tie Rod                      | Aluminum, 6061-T6    | 41               | 6.6           |

Table 2: Summary of FEA results for suspension and steering components

### 9.3.2 Tie rods

A similar analysis to that for the steering arm was used. Force was applied to one end of the tie rod while the other remained fixed. Both sides of the tie rod were tested with an applied force and fixed support.

## 9.4 Results

All FEA results for suspension and steering components are summarized in Table 2.

|  |      |                 |
|--|------|-----------------|
| Mass ( $M$ )                               | 550  | kg              |
| Wheelbase                                  | 2.60 | m               |
| Track                                      | 1.60 | m               |
| Tire Diameter                              | 0.53 | m               |
| Wheel Assembly Moment of Inertia ( $J_w$ ) | 0.25 | $\text{kg m}^2$ |
| Distance from Front Wheel to CoG ( $a$ )   | 1.32 | m               |
| Distance from Front Wheel to CoG ( $b$ )   | 1.28 | m               |
| Distance from Road to CoG ( $h$ )          | 0.52 | m               |
| Full Wheel Travel in Compression           | 45   | mm              |
| Front Coilover Angle from Vertical         | 40   | °               |
| Rear Coilover Angle from Vertical          | 30   | °               |

Table 3: Important vehicle parameters

## A Loading conditions

FEA of the chassis, suspension, and steering system was done using ANSYS software. Loading conditions were derived from both ASC requirements and real-world scenarios. Assuming a smooth driving surface, the largest normal force acting on the front tire will occur while braking in a turn. Similarly, the largest normal force acting on the rear tire will occur while accelerating in a turn. To approximate these loading condition, the a superposition of two static half car models is used; one for cornering and one for hard braking.

Table 3 lists vehicle parameters that are relevant in determining the loading conditions in the suspension. The mass and moment of inertia were computed using CAD software.

### A.1 Braking

Figure 19 shows a free body diagram of a half car model undergoing braking. The required braking force can be approximated as follows:

$$F_{\text{braking}} = F_{\text{Nf}} + F_{\text{Nr}} = Mg = (550 \text{ kg})(9.81 \text{ m s}^{-2}) = 5.40 \text{ kN} \quad (1)$$

From Figure 19, summing the moments about the centre of gravity and the vertical forces results in the following equations:

$$aF_{\text{Nf}} = hF_{\text{braking}} + bF_{\text{Nr}} \quad (2)$$

$$F_{\text{Nf}} + F_{\text{Nr}} = Mg \quad (3)$$

Solving for the front normal force:

$$\begin{aligned} aF_{\text{Nf}} &= hF_{\text{braking}} + b(Mg - F_{\text{Nf}}) \\ F_{\text{Nf}} &= \frac{hF_{\text{braking}} + bMg}{a + b} = \frac{(0.52 \text{ m})(5.40 \text{ kN}) + (1.28 \text{ m})(550 \text{ kg})(9.81 \text{ m s}^{-2})}{(1.32 \text{ m}) + (1.28 \text{ m})} = 3.74 \text{ kN} \end{aligned} \quad (4)$$

Note that 3.74 kN is for both front wheels. Therefore there is approximately 1.87 kN of normal force on each front tire during hard braking.

### A.2 Acceleration

MSXII uses NGM SCM-150 motors which have a peak torque of 135 N m. From this torque value and a number of other vehicle parameters the vehicle's maximum acceleration can be calculated as follows:

$$a = \frac{F_w}{\frac{1}{2}M} \quad (5)$$

$$\alpha_w = \frac{T_m - F_w r}{J_w} \quad (6)$$

$$\alpha_w = ar \quad (7)$$

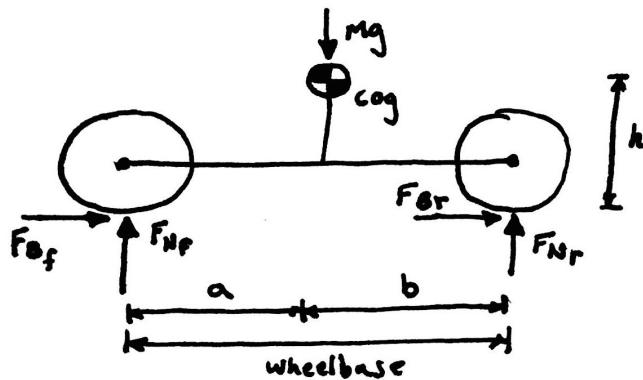


Figure 19: Free body diagram of vehicle braking

where  $a$  is the acceleration of the vehicle,  $F_w$  is the friction force acting on a single tire while accelerating,  $J_w$  is the moment of inertia of the wheel assembly,  $r$  is the radius of the tire,  $T_m$  is the torque from the motor and  $\alpha_w$  is the angular acceleration of the wheel.

Rearranging the above three equations, the acceleration of the vehicle can be expressed as a function of motor torque as follows:

$$a = \frac{T_m r}{\frac{1}{2} M r^2 + J_w}$$

$$a = \frac{(135 \text{ N m})(0.27 \text{ m})}{\frac{1}{2}(550 \text{ kg})(0.27 \text{ m}^2)^2 + 0.25 \text{ kg m}^2} = 1.80 \text{ m s}^{-2} \quad (8)$$

Solving for friction force on a single rear tire:

$$F_w = Ma = (550 \text{ kg})(1.80 \text{ m s}^{-2}) = 990 \text{ N} \quad (9)$$

The resulting normal force on the rear wheels can be calculated as follows:

$$bF_{Nr} = hF_w + a(Mg - F_{Nr})$$

$$F_{Nr} = \frac{hF_w + aMg}{a + b} = \frac{(0.52 \text{ m})(990 \text{ N}) + (1.32 \text{ m})(550 \text{ kg})(9.81 \text{ m s}^{-2})}{(1.32 \text{ m}) + (1.28 \text{ m})} = 2.94 \text{ kN} \quad (10)$$

Note that 2.94 kN is for both rear wheels. Therefore there is approximately 1.47 kN of normal force on each rear tire during maximum acceleration.

### A.3 Cornering

ASC regulations require simulations of a 1G turn, at minimum. This corresponds to the following lateral force:

$$F_{steer} = Mg = (550 \text{ kg})(9.81 \text{ m s}^{-2}) = 5.40 \text{ kN} \quad (11)$$

Additionally, the diameter of several highway exit ramps around the University of Waterloo were measured on satellite maps. The recommended speed limit on these exits is  $50 \text{ km h}^{-1}$ . Assuming a worst case scenario where the vehicle takes an exit with a 100 m diameter at  $80 \text{ km h}^{-1}$  ( $22.22 \text{ m s}^{-1}$ ), the required lateral force required to navigate this corner can be found as follows:

$$F_{steer} = \frac{Mv^2}{r} = \frac{(550 \text{ kg})(22.22 \text{ m s}^{-1})^2}{50 \text{ m}} = 5.43 \text{ kN} \quad (12)$$

This corresponds nearly identically to a 1G turn. Since the lateral force required in the second scenario is slightly higher, 5.34 kN will be used as the worst case cornering force.

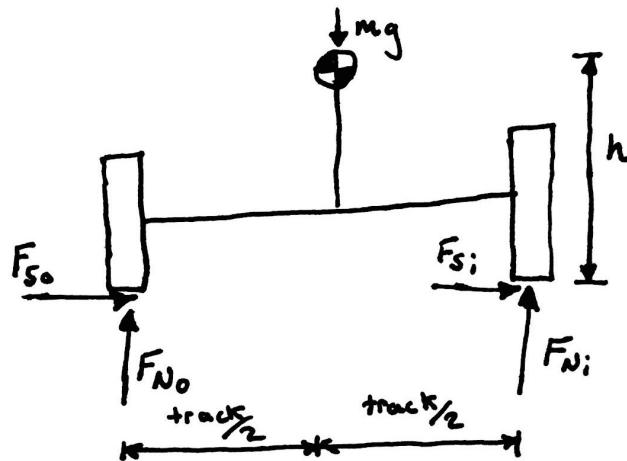


Figure 20: Free body diagram of vehicle cornering

Using the half car model shown in Figure 20, summing the moments about the centre of gravity and the vertical forces results in the following equations:

$$\frac{1}{2}L_{\text{track}}F_{\text{No}} = hF_{\text{steer}} + \frac{1}{2}L_{\text{track}}F_{\text{Ni}} \quad (13)$$

$$F_{\text{No}} + F_{\text{Ni}} = Mg \quad (14)$$

Solving for the outside wheel normal force:

$$\begin{aligned} \frac{1}{2}L_{\text{track}}F_{\text{No}} &= hF_{\text{steer}} + \frac{1}{2}L_{\text{track}}(Mg - F_{\text{Ni}}) \\ F_{\text{No}} &= \frac{hF_{\text{steer}} + \frac{1}{2}L_{\text{track}}Mg}{L_{\text{track}}} = \frac{(0.52 \text{ m})(5.43 \text{ kN}) + (0.80 \text{ m})(550 \text{ kg})(9.81 \text{ m s}^{-2})}{1.60 \text{ m}} = 4.46 \text{ kN} \end{aligned} \quad (15)$$

Solving for the inside wheel normal force:

$$F_{\text{Ni}} = Mg - F_{\text{No}} = (550 \text{ kg})(9.81 \text{ m s}^{-2}) - 4.46 \text{ kN} = 0.93 \text{ kN} \quad (16)$$

Note that the forces above are for both front and rear outside wheels. Assuming the force is evenly split between the front and rear, there is approximately 2.23 kN of normal force on each outside tire and 0.47 kN for each inside tire during maximum cornering.

#### A.4 Bump

As stipulated in the ASC 2018 regulations, the analysis for suspension and steering must include loading considerations for a 2G bump. We interpret this requirement as the body of the vehicle accelerating upwards at 2G, in which case the additional normal force subjected to a single tire can be expressed as follows:

$$F_{\text{N,bump}} = \frac{2Mg}{4} = \frac{2(9.81 \text{ m s}^{-2})(550 \text{ kg})}{4} = 2.70 \text{ kN} \quad (17)$$

#### A.5 Superposition

The braking, accelerating, and cornering conditions subject the wheels to normal forces that differ from those experienced when the car is at rest. The change in normal force for each loading condition can be expressed

as follows:

$$\Delta F_{Nf,\text{braking}} = F_{Nf,\text{braking}} - \frac{Mg}{4} = 1.87 \text{ kN} - 1.35 \text{ kN} = 0.52 \text{ kN} \quad (18)$$

$$\Delta F_{Nr,\text{accelerating}} = F_{Nr,\text{accelerating}} - \frac{Mg}{4} = 1.47 \text{ kN} - 1.35 \text{ kN} = 0.12 \text{ kN} \quad (19)$$

$$\Delta F_{No,\text{cornering}} = F_{No,\text{cornering}} - \frac{Mg}{4} = 2.23 \text{ kN} - 1.35 \text{ kN} = 0.88 \text{ kN} \quad (20)$$

$$\Delta F_{Ni,\text{cornering}} = F_{Ni,\text{cornering}} - \frac{Mg}{4} = 0.47 \text{ kN} - 1.35 \text{ kN} = -0.88 \text{ kN} \quad (21)$$

$$\Delta F_{N,\text{bump}} = F_{N,\text{bump}} - \frac{Mg}{4} = 2.70 \text{ kN} - 1.35 \text{ kN} = 1.35 \text{ kN} \quad (22)$$

To approximate the worst case loading condition, a superposition of the changes in normal force and the nominal normal force is applied. Note that the nominal force used is the same for each wheel, which assumes a centre of gravity approximately centred along the wheelbase.

$$F_{Nfi,\text{max}} = \Delta F_{Nf,\text{braking}} + \Delta F_{Ni,\text{cornering}} + 2F_{N,\text{nominal}} = 0.52 \text{ kN} - 0.88 \text{ kN} + 2.70 \text{ kN} = 2.34 \text{ kN} \quad (23)$$

$$F_{Nfo,\text{max}} = \Delta F_{Nr,\text{braking}} + \Delta F_{No,\text{cornering}} + 2F_{N,\text{nominal}} = 0.12 \text{ kN} - 0.88 \text{ kN} + 2.70 \text{ kN} = 4.10 \text{ kN} \quad (24)$$

$$F_{Nri,\text{max}} = \Delta F_{Nf,\text{braking}} + \Delta F_{Ni,\text{cornering}} + 2F_{N,\text{nominal}} = 0.52 \text{ kN} + 0.88 \text{ kN} + 2.70 \text{ kN} = 1.94 \text{ kN} \quad (25)$$

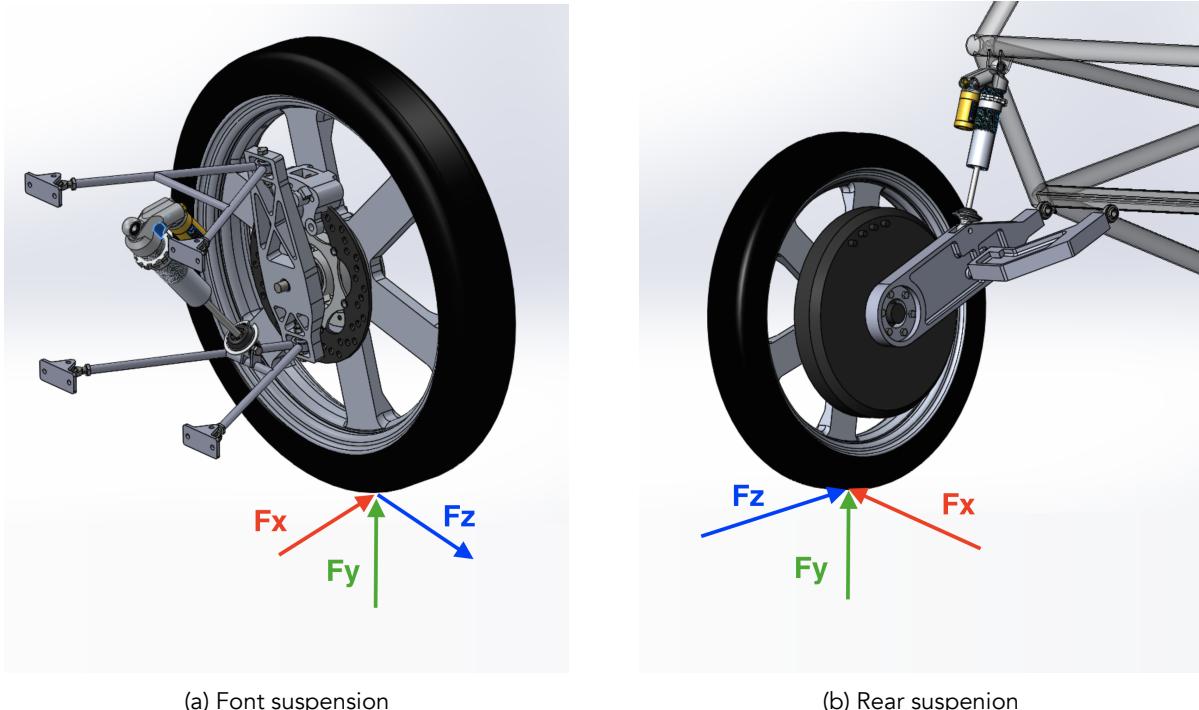
$$F_{Nro,\text{max}} = \Delta F_{Nr,\text{braking}} + \Delta F_{No,\text{cornering}} + 2F_{N,\text{nominal}} = 0.12 \text{ kN} + 0.88 \text{ kN} + 2.70 \text{ kN} = 3.70 \text{ kN} \quad (26)$$

## A.6 Summary

Table 4 summarizes the loading conditions used for static structural FEA simulations on the suspension and steering components. Note that the direction of the force corresponds with the global coordinate system of the MSXII and the vectors shown in Figure 21. The assemblies shown are for the driver's side of the vehicle

Table 4: Summary of worst case loading conditions

| Worst Case Loading                            | $F_x$ (kN) | $F_y$ (kN) | $F_z$ (kN) |
|---|------------|------------|------------|
| Braking & Cornering (Inside Front Wheel)      | 2.72       | 2.34       | 2.70       |
| Braking & Cornering (Outside Front Wheel)     | -2.72      | 4.10       | 2.70       |
| Accelerating & Cornering (Inside Rear Wheel)  | 2.72       | 1.94       | 0.99       |
| Accelerating & Cornering (Outside Rear Wheel) | -2.72      | 3.70       | 0.99       |



(a) Front suspension

(b) Rear suspension

Figure 21: Suspension coordinate system

## B FEA images for chassis and door

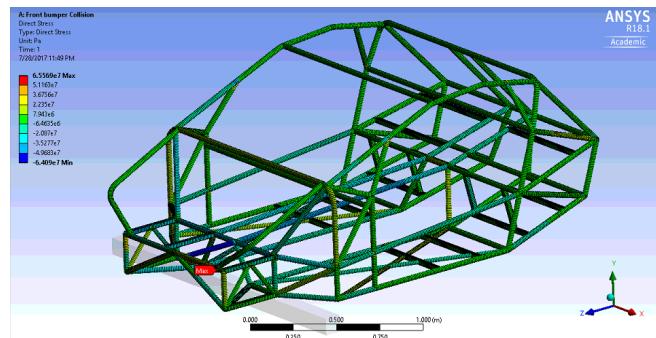


Figure 22: Front bumper collision

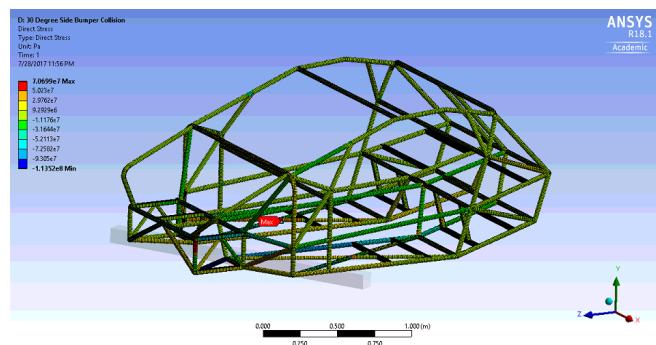


Figure 23: Front bumper 30 degree collision

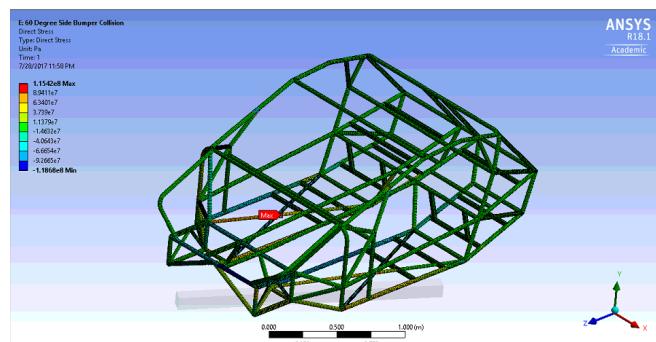


Figure 24: Front bumper 60 degree collision

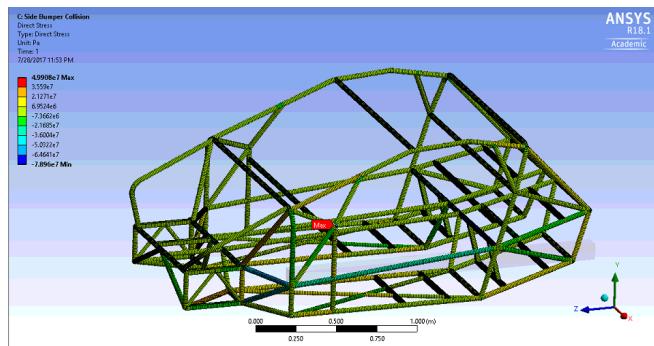


Figure 25: Side bumper collision

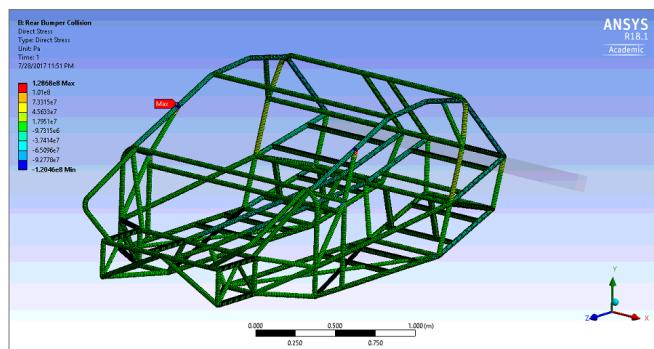


Figure 26: Rear bumper collision

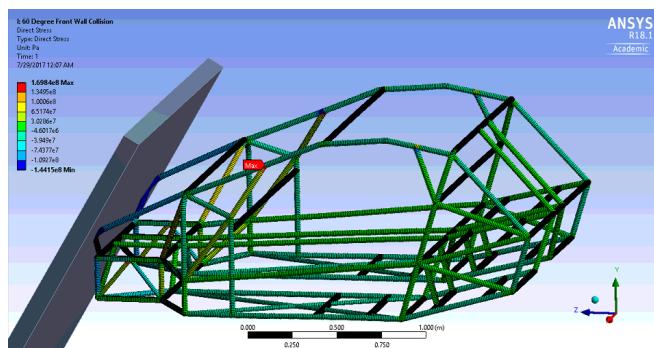


Figure 27: Hood 60 degree collision

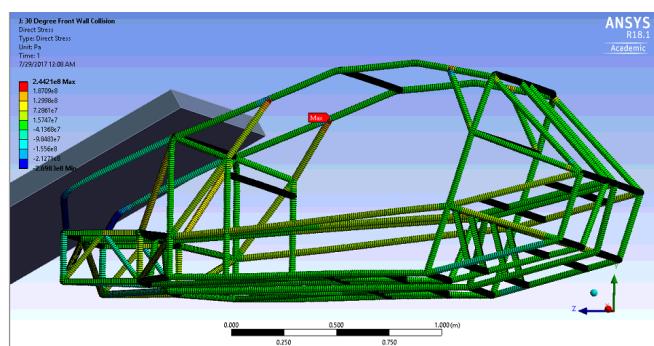


Figure 28: Hood 30 degree collision

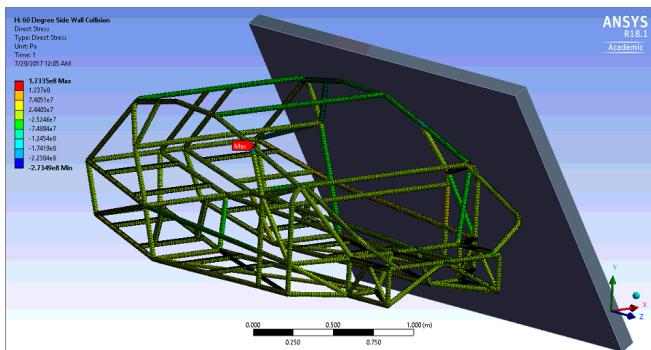


Figure 29: Side 60 degree collision

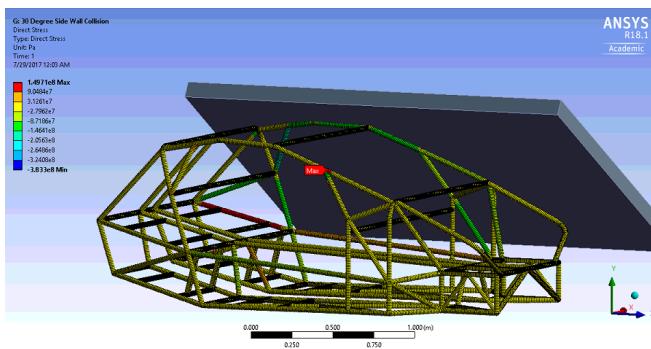


Figure 30: Side 30 degree collision

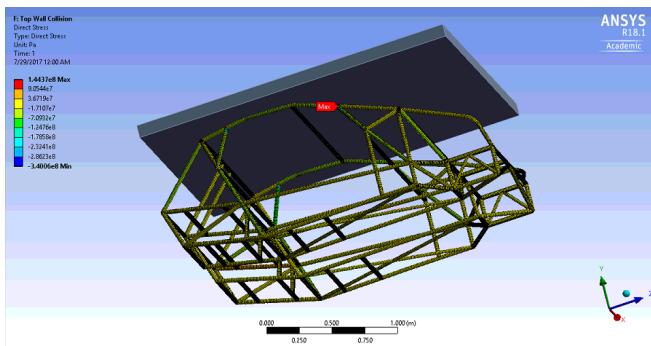


Figure 31: Roof top collision

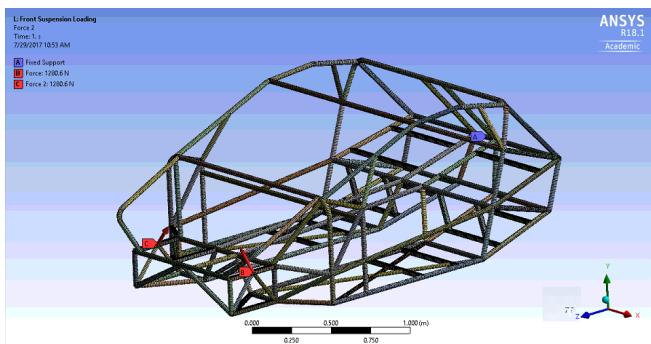


Figure 32: Vehicle rest front subframe loading

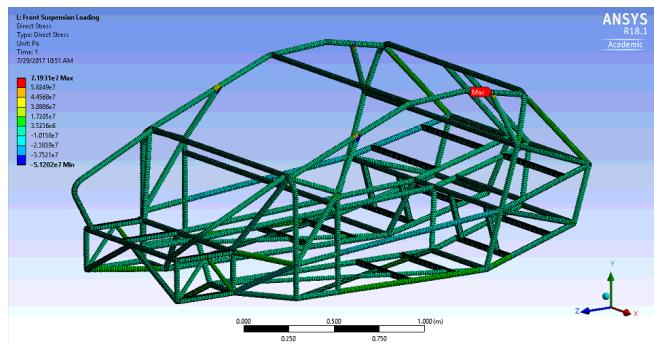


Figure 33: Vehicle rest front subframe stress

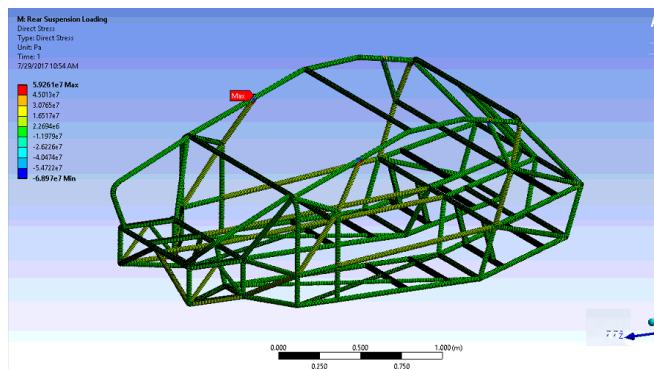


Figure 34: Vehicle rest rear subframe stress

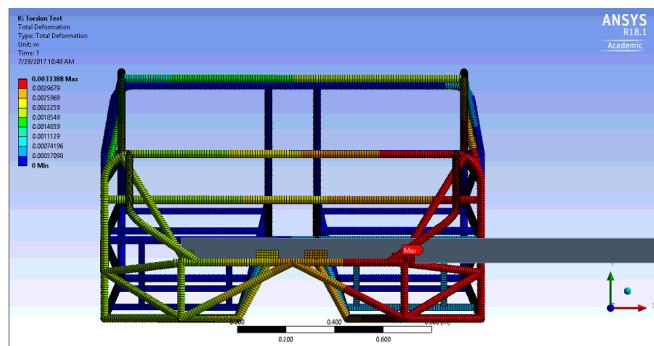


Figure 35: Torsion test, deformation

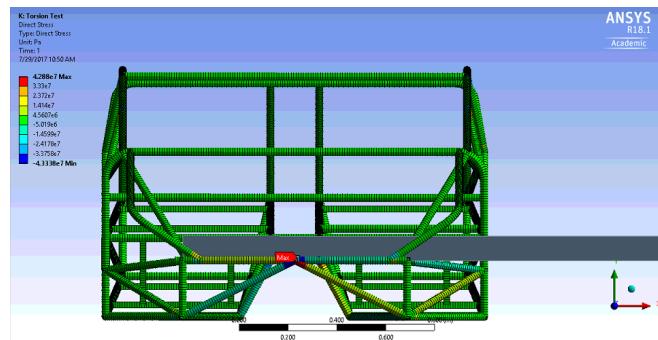


Figure 36: Torsion test, stress

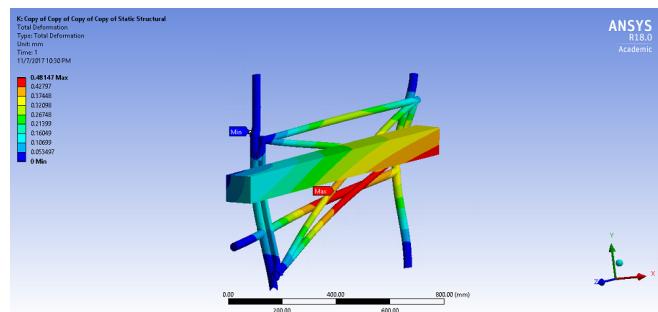


Figure 37: Door side impact displacement

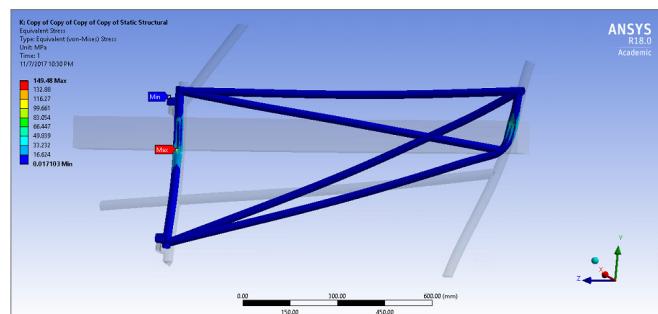


Figure 38: Door side impact stress

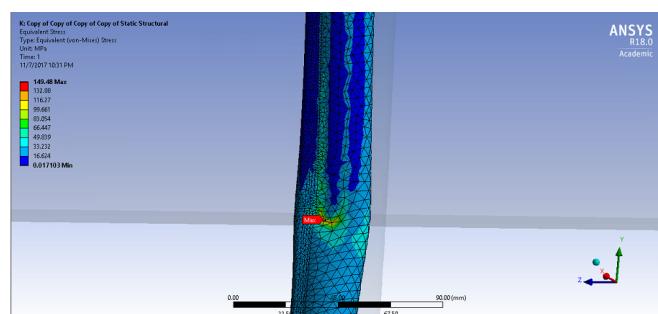


Figure 39: Door side impact stress, zoomed

## C FEA images for suspension and steering

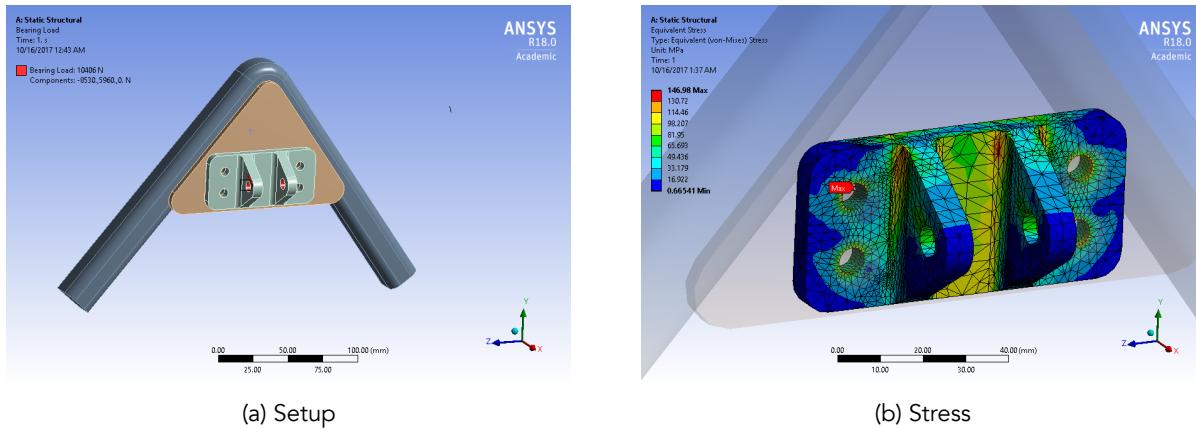


Figure 40: Coilover clevis

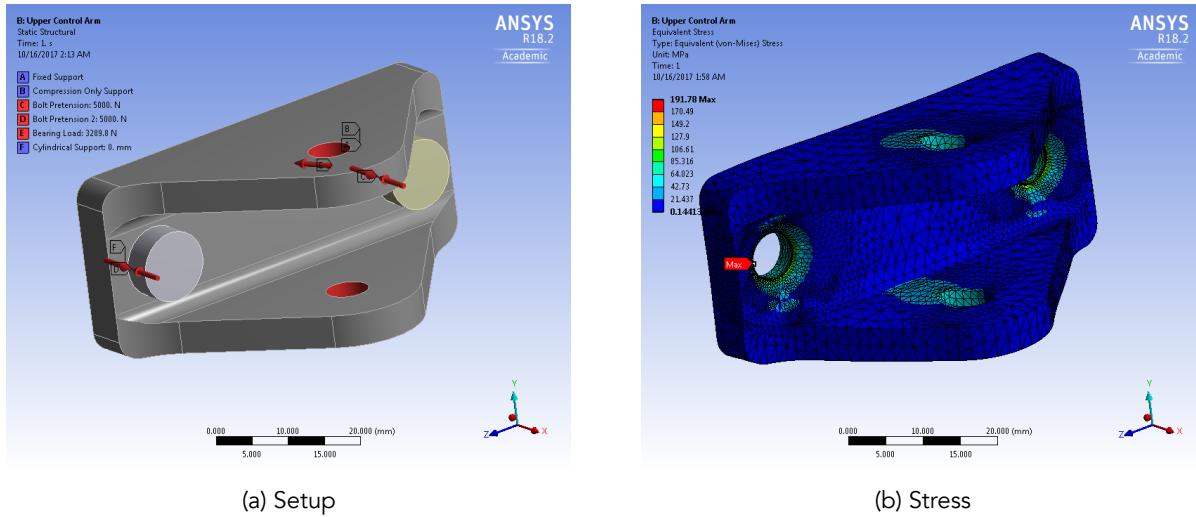


Figure 41: Upper control arm clevis

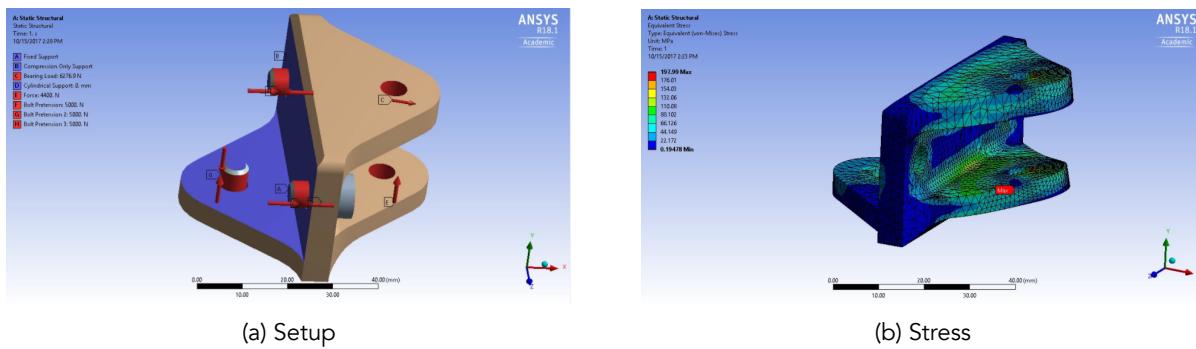


Figure 42: Lower control arm clevis

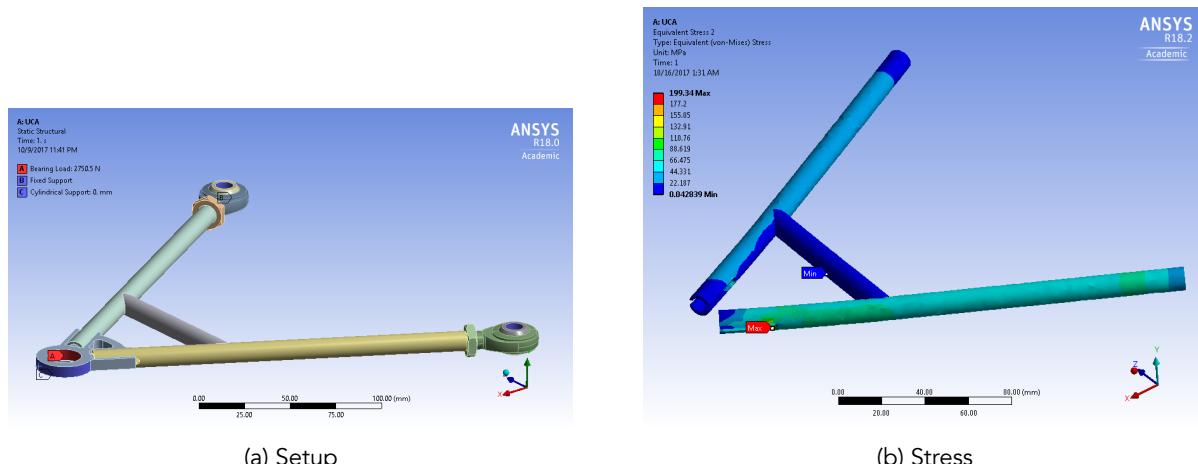


Figure 43: Upper control arm

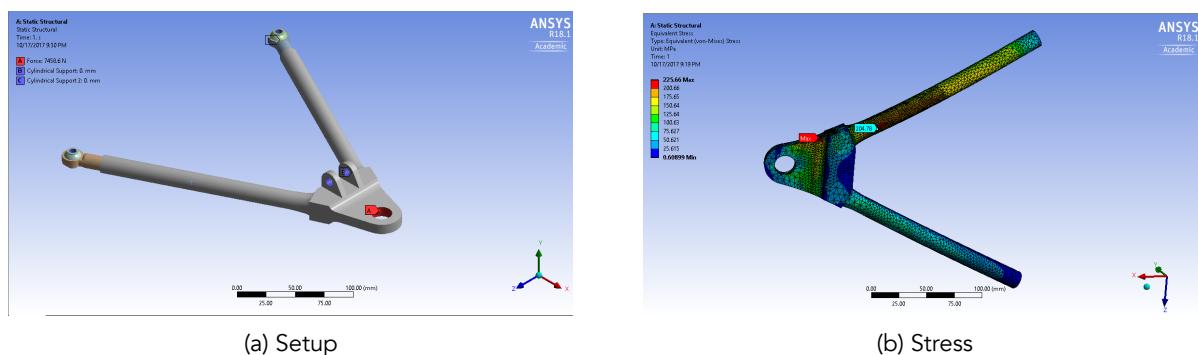


Figure 44: Lower control arm

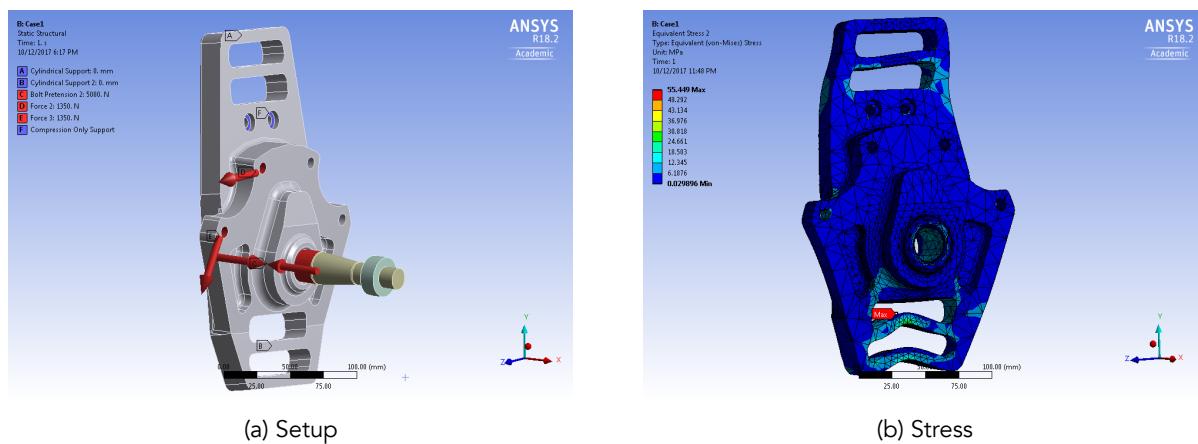


Figure 45: Upright

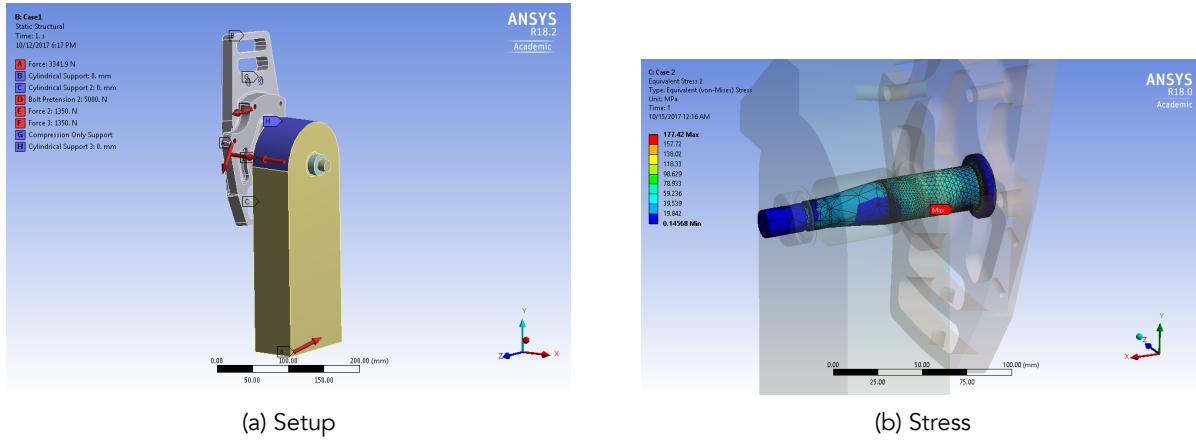


Figure 46: Spindle

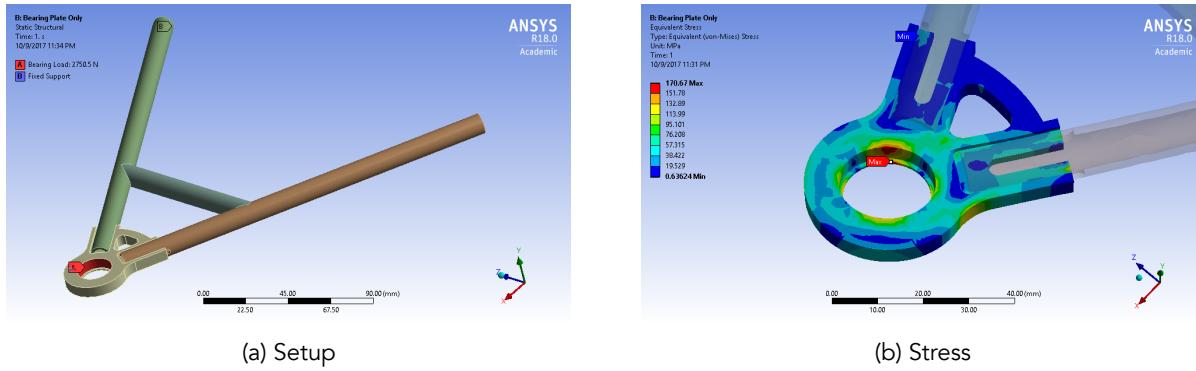


Figure 47: Upper bearing plate

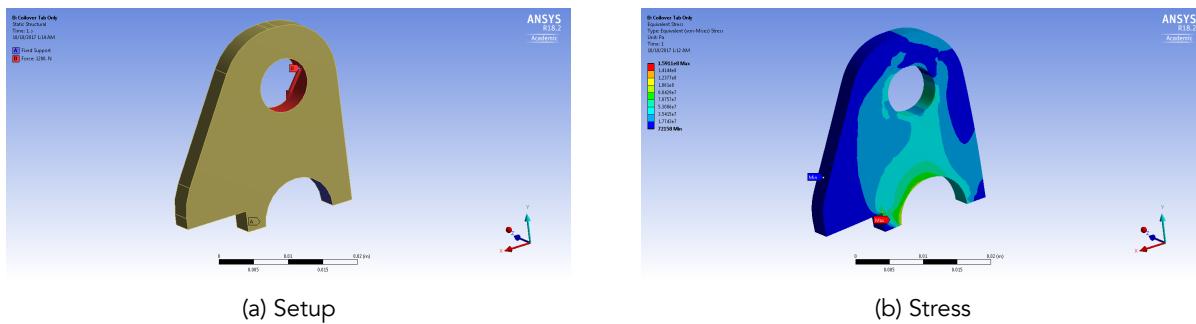


Figure 48: Coilover control arm tab

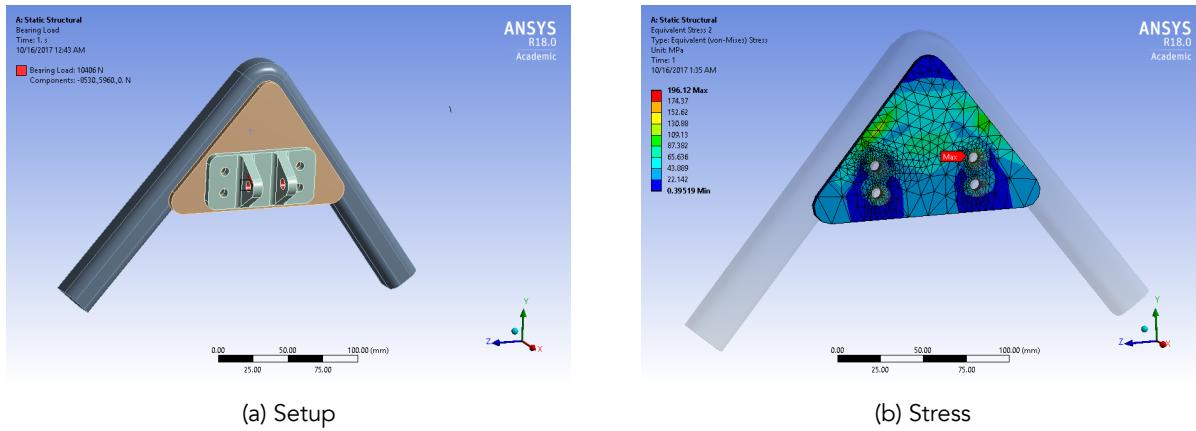


Figure 49: Coilover mounting plate

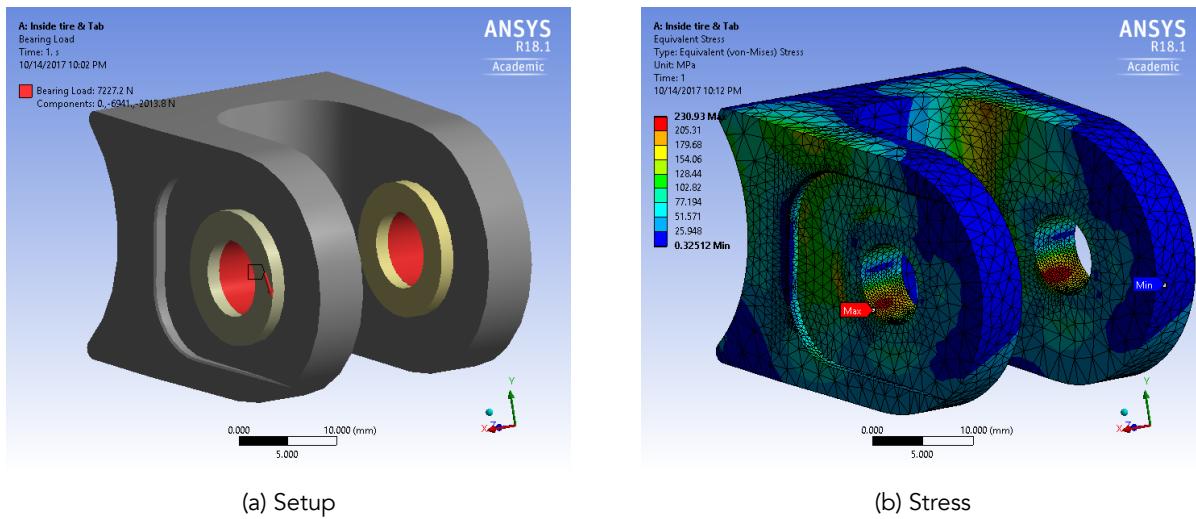


Figure 50: Rear suspension clevis

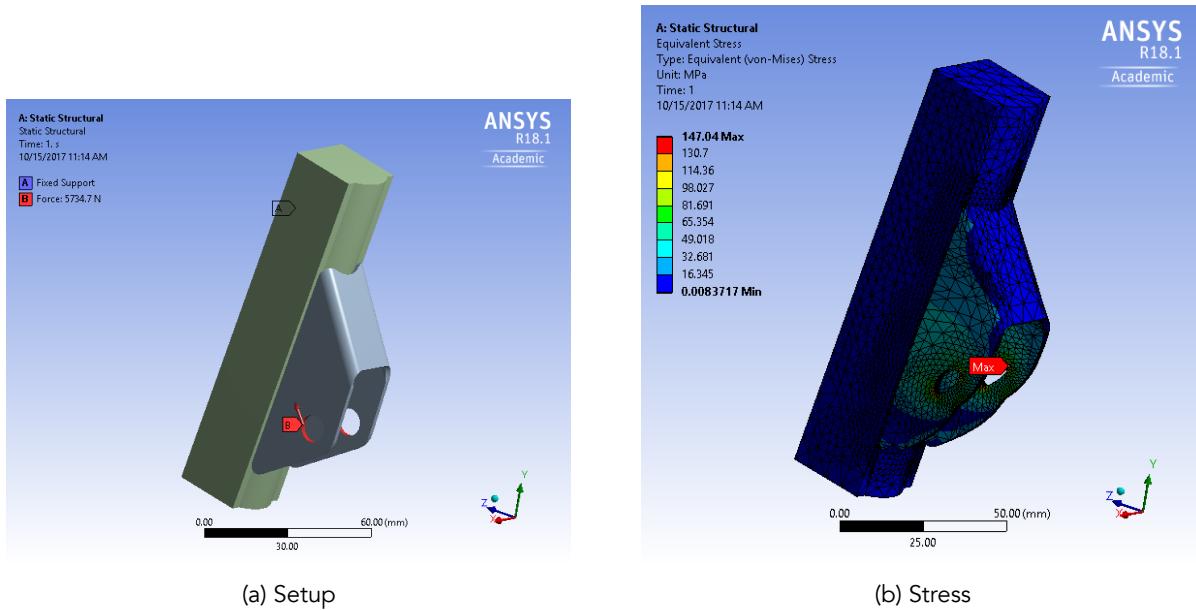


Figure 51: Rear suspension coilover tab

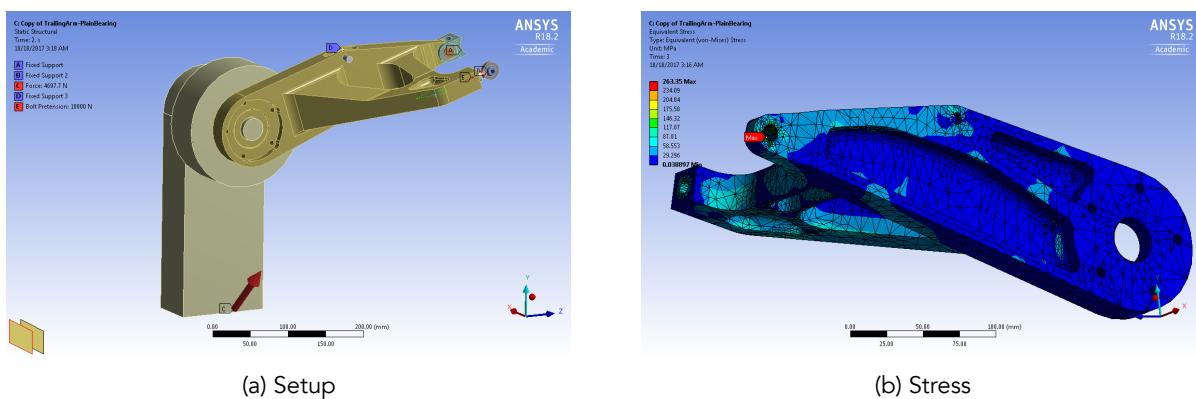


Figure 52: Trailing arm

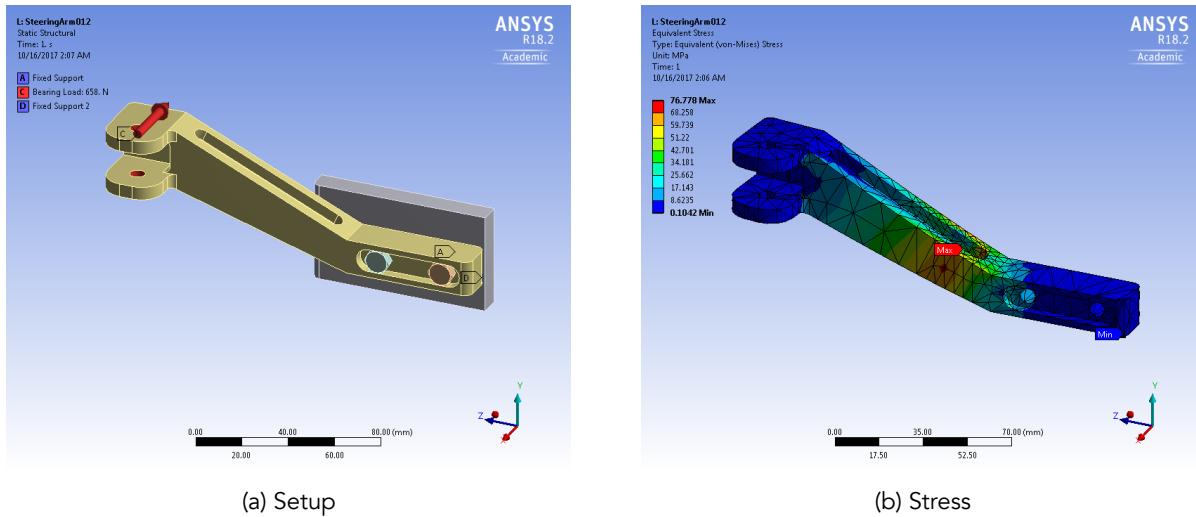


Figure 53: Steering arm

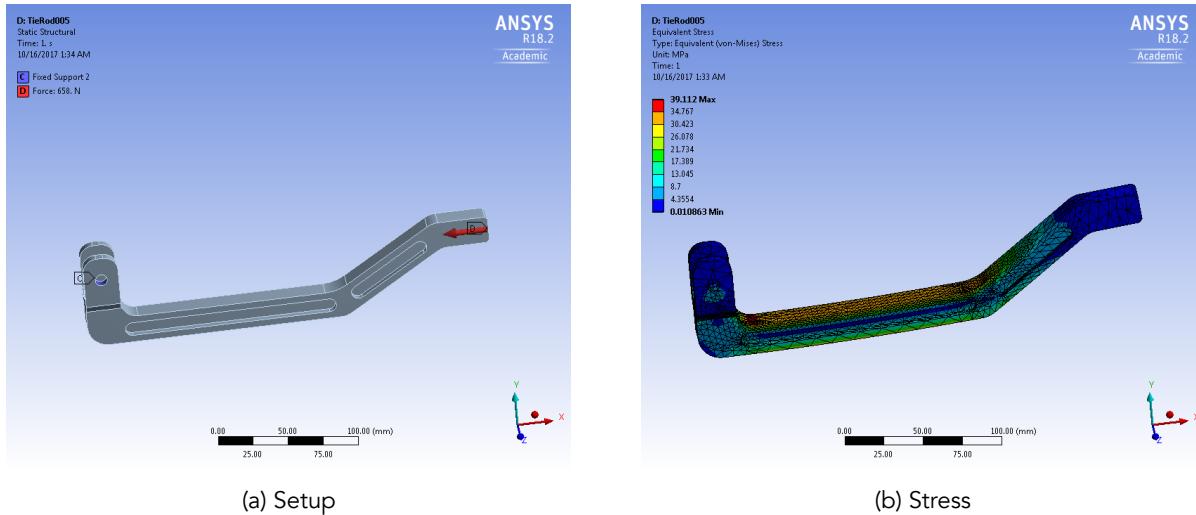


Figure 54: Tie rod