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Electric Vehicle Steering System Optimization

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Electric Vehicle Steering System Optimization

by

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Abstract

One of the tasks for the MAE 491 Senior Design course is to design and build a working steering system of a single-seat race car for the Formula SAE Electric Vehicle competition. This system includes the steering wheel, steering linkages, steering rack, and tie rods, which connect to the suspension uprights. It is necessary for the steering wheel, linkages, and rack to be rigidly mounted and supported by the chassis. During normal vehicle operation in the FSAE events, the steering linkages will experience large forces and torques from the driver and the tires. The system needs to have a balance of rigidity and weight to provide adequate driver feedback while also being light. The design of these linkages and support/mounting structures will benefit from a series of Finite Element Analyses (FEA's). This project will investigate these steering components with regards to strength, rigidity, and weight to mechanically improve and optimize the steering system design. Results obtained will be useful for current and future students of the senior design class as they further improve the vehicle's design.

Introduction

The steering system of the race car converts rotational motion of the steering wheel into linear motion of the tie rods through the use of a rack and pinion. The forces that travel through these tie rods push one wheel and pull the other, causing the vehicle to turn. A basic example of this is illustrated in Figure 1.

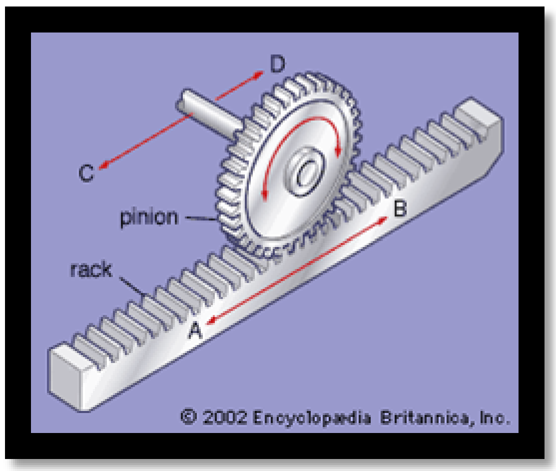

Figure 1: Basics of a Steering Rack [1]

The behavior of the system is dependent on the geometry of the front suspension members. The current suspension design is simplistic, and lacks kingpin inclination, caster angle, and caster trail. These variables impact the "feel" of steering immensely, and can lead to large, sudden torques at the steering wheel that the driver would have to resist [2]. Because the vehicle is in such an early stage of development, this paper will ignore the previously mentioned variables, dealing with the suspension system as little as possible. The main purpose of this paper is to verify the structural integrity of the steering components, and make sure that ongoing design is heading in the right direction. To this effect, three components of the steering system that experience the largest loads have been selected for analysis: the steering supports, tie rods, and the steering rack mounting plate.

Steering Supports

The steering supports are used to keep the steering column in its desired location. This is done by having two steel tubes support a plate-mounted bearing which confines the steering column. Figure 2 depicts the supports in their desired location on the vehicle's chassis.

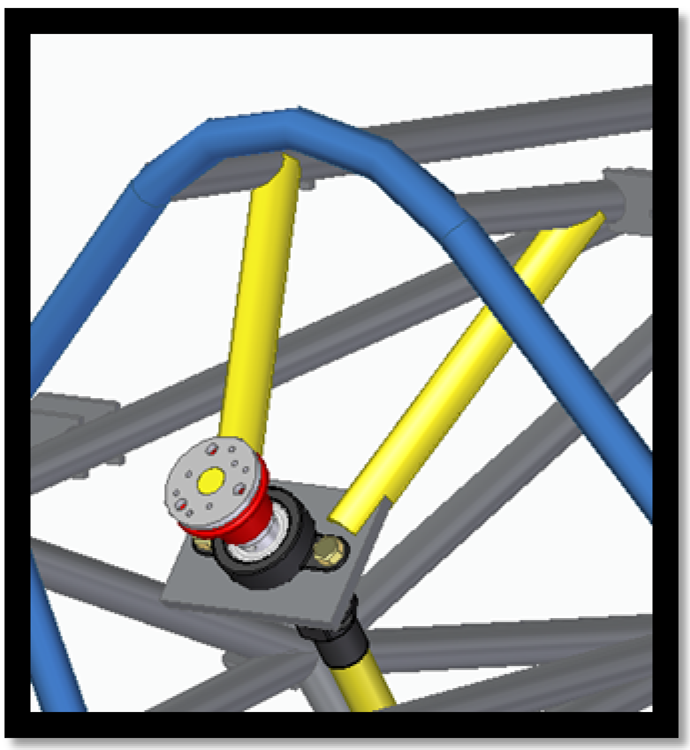

Figure 2: Mounted Steering Supports (shown in yellow)

In this configuration, lateral loads applied to the steering wheel by the driver would cause the highest stress within the steel tubes, making them act similar to a cantilevered beam. In order to make sure the supports could withstand these loads, two different tube sizes were examined:

1. ⅝” Outer Diameter, 0.0625” Steel Wall Tube

2. ¾” SCH 40 Structural Steel Pipe

Tie Rods

The tie rods are joined to either end of the steering rack using heim-joints and clevises. On the outer ends of the tie rods, heim-joints are used to connect them to the front suspension uprights. The assembly is shown in Figure 3.

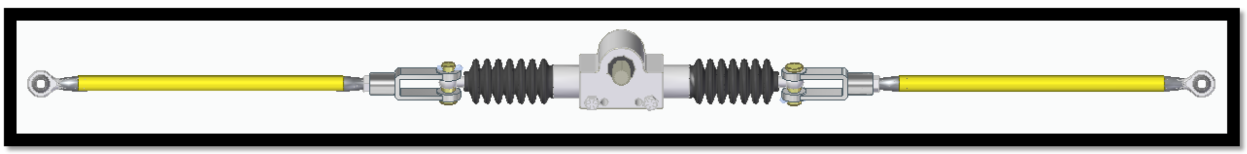

Figure 3: Current Steering Rack with Tie Rods

Steering Rack Mounting Plate

The steering rack must be rigidly mounted to the chassis in order to work properly and minimize any play in the steering system. If its position were to change during operation, the carefully designed steering geometry would be compromised. Since some of the moment experienced by the steering rack pinion while turning the steering wheel would be transferred into the mounting plate, it is critical to verify its strength. The current design has the steering rack mounted to a 0.15” aluminum plate using two Grade 8 Steel, 5/16"-18 bolts, shown in Figure 4. The plate itself is mounted to the chassis using three weld tabs.

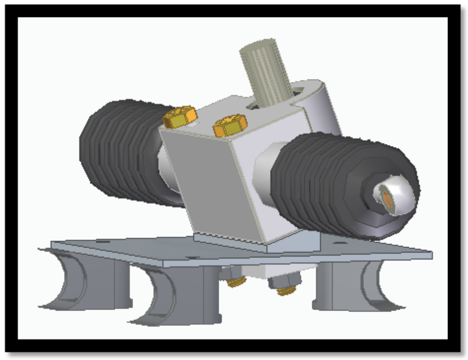

Figure 4: Steering Rack Mounted on Aluminum Plate

Background Research

It is widely accepted that the steering system should be able to tolerate much more load than it is expected to experience during operation in order to keep the driver safe. One study led by an SAE Industrial Lecturer Steve Fox examined the average torques exhibited by students in a FSAE car, and found that any competing car should be able to withstand a steering torque of 75-100 ft-lbs [3]. While no student was able to exert these loads during the testing, it is said that one should “never underestimate the strength of a scared driver” [3]. Using the larger torque and the radius of UAH’s current steering rack’s pinion, the minimum necessary force for the tie rods to withstand can be found by:

$$F = T/r$$

$$F = \frac{100\,ft{-}lb}{(5/8\,in)}\left[\frac{12\,in}{ft}\right]$$

$$F = 1920\,lb$$

This value can be compared with the estimated maximum load that the steering system is expected to experience. The largest force incurred by the steering components would occur during cornering, when the tires are experiencing a large amount of horizontal force. The UAH Suspension subteam during the 2023-2024 academic year approximated the max horizontal cornering force on the front upright to be just over 15,000 N [4]. Due to the vehicle being in its early stages of development, this value can only be considered an estimation.

Most of the horizontal cornering force on the front upright would be resisted by the top and bottom A-Arms, which attach to the vehicle's chassis and help keep the wheels aligned. For now, it will be assumed that half of the horizontal cornering force will be resisted by the steering tie rods, even though this is a vast overestimation. Converting this into English units, a force of 1,686 lb is found. This means the maximum expected force on the steering components is less than the minimum force recommended by SAE Lecturers. To be safe, the higher load values will be used during the analysis stage.

Analysis

For each component of the steering system, a Finite Element Analysis was run to see how it would react to expected loads that it would experience during normal operation. First, a parametric solid model from SolidEdge was imported into a Patran database. These models were created throughout the year as part of the Senior Design class. Due to the inaccuracies of modeling thin, 3D elements in Patran, a 2D midplan surface was created for each component, and a mesh with a Global Edge Length (GEL) of 0.1 was applied. The thickness of each component was input into its respective Properties table. Skew tests were performed to verify the strength of each mesh (Appendix A). For each model, multiple load cases were tested. The first had the model experience a realistic loading scenario that the component is likely to see during competition. The rest were validity checks, whose purposes are to make sure the model is mathematically accurate [5]. These checks included the following:

1. Dedicated Load Test: Checks the model for small deformation and residuals.
2. Unit Displacement Test: Makes sure that no illegal grounding exists within the model.
3. Free Free Test: Verifies that the model is a rigid body when unconstrained.
4. Unit Temperature Test: Verifies the model behaves accurately under temperature loading.
5. Unit Gravity Test: Verifies that the responds correctly to inertial loading. The single point constraint forces should add up to the total weight of the model.

Results for each were compiled in an Excel file for analysis. Patran's estimation of the model's weight was compared to real life calculations using the model's known volume and specific density. Deflection values from the Dedicated Load Test and the Unit Temperature Test were compared with calculated values using the following formulas:

$$\Delta L = \alpha L_o \Delta T$$

$$\delta_{max} = \frac{PL^3}{3EI}$$

Steering Supports

Testing the steering supports involved placing lateral loads at a specified distance from the tubes. These forces imitated how a driver might yank sideways on the steering wheel, or place their weight on the wheel when entering/exiting the vehicle. The previously mentioned article by Steve Fox recommends the steering column withstand at least 150 lb of lateral force [3].

GENERAL STEEL PROPERTIES	
Modulus of Elasticity (ksi)	29000
Yield Stress (psi)	50800
Ultimate Stress (psi)	60900
CTE (in / in-°F)	6.50E-06
Specific Weight (lb/in^3)	0.2855
Reference Temp (°F)	32
Poisson's Ratio	0.25

Figure 5: Steel Material Properties [6]

Both steering support models were given the material properties of general steel, shown in Figure 5. An inertial load was applied on the model to simulate Earth's gravity. RBE2 elements were used to apply a zero displacement boundary condition along the welded edges, as well as the lateral force exerted on the other end, shown in Figure 6. Since a 150 lb lateral load would be resisted by both the left and right steering support, only a 75 lb force was applied onto each model.

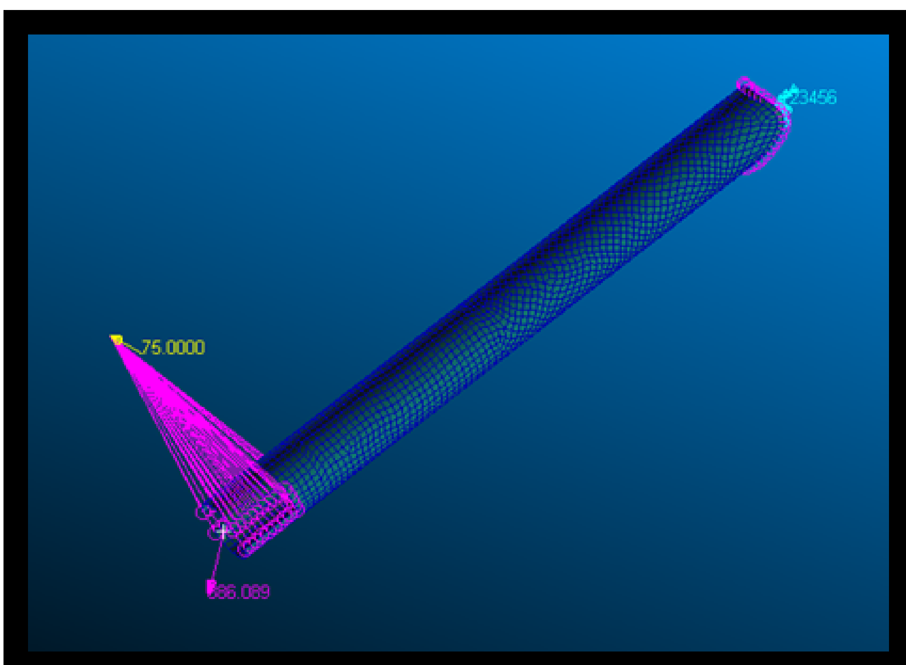

Figure 6: Steering Support Operational Load Case

Tie Rods

In order to make finite element analysis on the tie rods simpler, their structures were idealized as a simple tube. This excludes the heim-joints which attach to the front uprights, the bung adapters on both sides, and the clevis joint. The material properties of the tie rods were assumed to be the same as the steering supports, shown in Figure 5. A 2D Shell property with a thickness of 0.0625" was applied to the created midplane surface. RBE2 elements were used to apply a zero displacement boundary condition at one end of the model, and the previously calculated axial load of 1920 lb at the other. Tests were performed applying the load in both tension and compression. The Patran setup is shown in Figures 7 and 8.

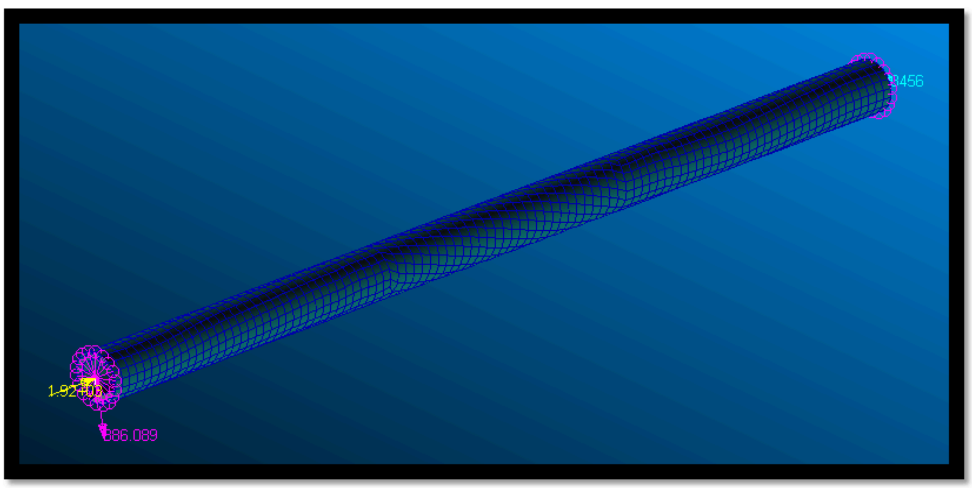

Figure 7: Tie Rod Operational Load Case (Compression)

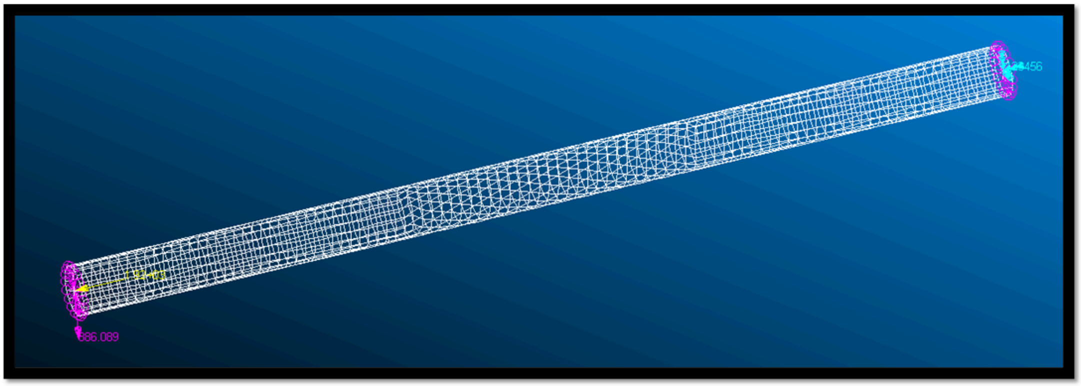

Figure 8: Tie Rod Operational Load Case (Tension)

The critical buckling load can also be found using Euler's Buckling Formula, shown by:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} = \frac{\pi^2 E}{(KL)^2} * \frac{\pi}{64}(D^4 - d^4)$$

$$P_{cr} = \frac{\pi^2 (29{,}000{,}000\ psi)}{(1*10.151\ in)^2} * \frac{\pi}{64}(0.625^4 - 0.5^4)\ in^4$$

$$P_{cr} = 12,283\ lb$$

This load is far larger than the expected force going into the tie rod, showing it is not likely the tie rod would critically fail during operation.

Steering Rack Mounting Plate

An aluminum material property was created using the values in Figure 9, and applied to the meshed model of the mounting plate, along with a thickness of 0.15". Five RBE2 elements were created: three for zero displacement boundary conditions, and two for applying torques to the plate. The first three model locations where the plate is bolted into the chassis. The latter two transfer the total torque experienced by the rack pinion into the plate. In reality, not all of the torque experienced by the rack's pinion will be resisted by the plate, but this analysis will model the worst case scenario. The Patran setup can be seen in Figure 10.

ALUMINUM 6061 PROPERTIES	
Modulus of Elasticity (ksi)	10000
Yield Stress (psi)	40000
Ultimate Stress (psi)	45000
CTE (in / in-°F)	1.35E-05
Specific Weight (lb/in^3)	0.0975
Reference Temp (°F)	32
Poisson's Ratio	0.33

Figure 9: Aluminum 6061 Material Properties [7]

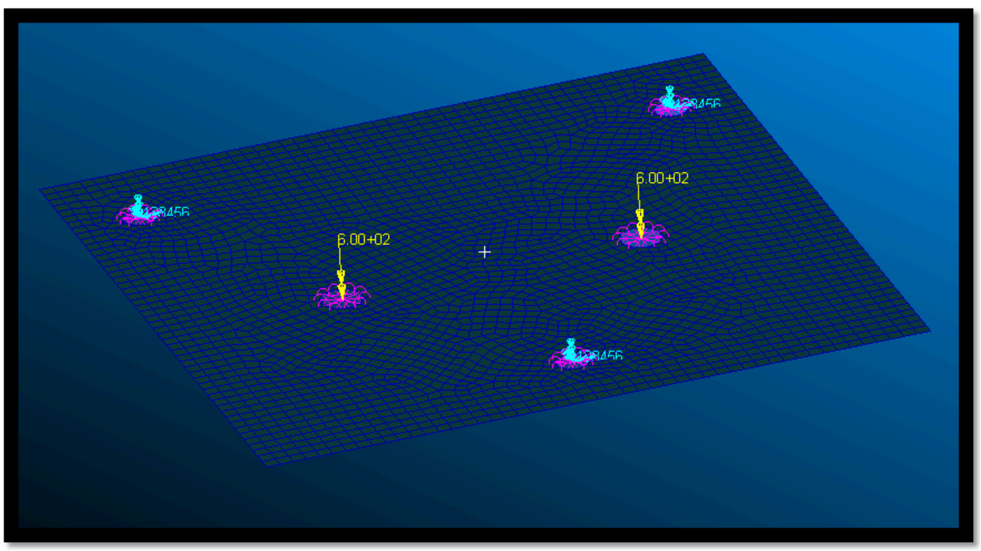

Figure 10: Mounting Plate Operational Load Case

Results

Steering Supports

	Max Stress (psi)	Max Displacement (in)	FS
Actual Load Case	12900	0.0204	3.9379845
Unit Displacement Test	1900000	1	0.02673684
Dedicated Load Case	13000	0.0204	3.90769231
Unit Temperature Test	40900	0.00611	1.24205379
Unit Gravity Test (X)	88.3	0.000076	575.311438
Unit Gravity Test (Y)	3.68	0.000000782	13804.3478
Unit Gravity Test (Z)	66.5	0.0000808	763.909774

Figure 11: Patran Stress, Deflection, and Factor of Safety (FS) Results for ¾" SCH 40 Steel Steering Supports

Unit Temp Hand Calcs			Lo (in)	9.5		
$\Delta L = \alpha L_o \Delta T$	ΔL (in) =		(These are rough estimations for CTE and Lo)			
	0.006175				**% Error =**	1.05%
Dedicated Load Hand Calcs		(approximation as a cantilever beam)				
$I = \frac{\pi(D^4 - d^4)}{64}$	0.037036326	$\delta_{max} = \frac{PL^3}{3EI}$	0.01995653			
					% Error =	2.22%
Weight Hand Calcs						
W = V * specific weight	0.902189202					
Patran Calculated Weight (lb)	8.63E-01				**% Error =**	4.37%
Free Free Test Results	SC1:FREEFREETEST, A2:Mode 1: Freq.=0.000540397					
	SC1:FREEFREETEST, A2:Mode 2: Freq.=0.000544377					
	SC1:FREEFREETEST, A2:Mode 3: Freq.=0.000959505					
	SC1:FREEFREETEST, A2:Mode 4: Freq.=0.00140641					
	SC1:FREEFREETEST, A2:Mode 5: Freq.=0.00177032					
	SC1:FREEFREETEST, A2:Mode 6: Freq.=0.00755666					
	SC1:FREEFREETEST, A2:Mode 7: Freq.=2583.36					
	SC1:FREEFREETEST, A2:Mode 8: Freq.=2588.24					
	SC1:FREEFREETEST, A2:Mode 9: Freq.=6335.89					
	SC1:FREEFREETEST, A2:Mode 10: Freq.=6385.29					

Figure 12: Validity Tests Percent Errors for ¾" SCH 40 Steel Steering Supports

	Max Stress (psi)	Max Displacement (in)	FS
Actual Load Case	46900	0.16	1.08315565
Unit Displacement Test	845000	1.01	0.06011834
Dedicated Load Case	46900	0.16	1.08315565
Unit Temperature Test	29100	0.00694	1.74570447
Unit Gravity Test (X)	78.4	0.000197	647.959184
Unit Gravity Test (Y)	3.36	0.000000741	15119.0476
Unit Gravity Test (Z)	74.6	0.000201	680.965147

Figure 13: Patran Stress, Deflection, and Factor of Safety (FS) Results for ⅝" OD Steel Steering Supports

Unit Temp Hand Calcs			Lo (in)	9.5		
$\Delta L = \alpha L_o \Delta T$	ΔL (in) =		(These are rough estimations for CTE and Lo)			
	6.18E-03				**% Error =**	12.39%
Dedicated Load Hand Calcs		(approximation as a cantilever beam)				
$I = \frac{\pi(D^4 - d^4)}{64}$	0.004422179	$\delta_{max} = \frac{PL^3}{3EI}$	0.1671385			
					% Error =	4.27%
Weight Hand Calcs						
W = V * specific weight	0.299558836					
Patran Calculated Weight (lb)	2.79E-01				**% Error =**	6.86%
Free Free Test Results	SC1:FREEFREETEST, A6:Mode 1: Freq.=0.000723973					
	SC1:FREEFREETEST, A6:Mode 2: Freq.=0.0011942					
	SC1:FREEFREETEST, A6:Mode 3: Freq.=0.00161218					
	SC1:FREEFREETEST, A6:Mode 4: Freq.=0.0016588					
	SC1:FREEFREETEST, A6:Mode 5: Freq.=0.00233773					
	SC1:FREEFREETEST, A6:Mode 6: Freq.=0.0157691					
	SC1:FREEFREETEST, A6:Mode 7: Freq.=1711.86					
	SC1:FREEFREETEST, A6:Mode 8: Freq.=1715.2					
	SC1:FREEFREETEST, A6:Mode 9: Freq.=4435.34					
	SC1:FREEFREETEST, A6:Mode 10: Freq.=4455.72					

Figure 14: Validity Tests Percent Errors for ⅝" OD Steel Steering Supports

Tie Rods

	Max Stress (psi)	Max Displacement (in)	FS
Actual Load case (Tension)	19100	0.00653	2.659685864
Actual Load Case (Compression)	19100	0.00653	2.659685864
Unit Displacement Test	250000	1	0.2032
Dedicated Load Case	70500	0.283	0.720567376
Unit Temperature Test	12700	0.0045	4
Unit Gravity Test (X)	128	0.000381	396.875
Unit Gravity Test (Y)	2.96	0.000000507	17162.16216
Unit Gravity Test (Z)	130	0.000381	390.7692308

Figure 15: Patran Stress, Deflection, and Factor of Safety (FS) Results for Tie Rods

Unit Temp Hand Calcs			Lo (in)	10.151		
$\Delta L = \alpha L_o \Delta T$	ΔL (in)		(These are rough estimations for CTE and Lo)			
	0.004486742				**% Error =**	0.30%
Dedicated Load Hand Calcs		(approximation as a cantilever beam)				
$I = \frac{\pi(D^4 - d^4)}{64}$	0.004422179	$\delta_{max} = \frac{PL^3}{3EI}$	0.271876026			
					% Error =	4.09%
Weight Hand Calcs						
W = V * specific weight	0.3200865					
Patran Calculated Weight (ll	2.99E-01				**% Error =**	6.46%
Free Free Test Results	SC1:FREEFREETEST, A4:Mode 1: Freq.=0.000396138					
	SC1:FREEFREETEST, A4:Mode 2: Freq.=0.000686681					
	SC1:FREEFREETEST, A4:Mode 3: Freq.=0.00124885					
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	SC1:FREEFREETEST, A4:Mode 5: Freq.=0.00153322					
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	SC1:FREEFREETEST, A4:Mode 7: Freq.=1246.95					
	SC1:FREEFREETEST, A4:Mode 8: Freq.=1247.42					
	SC1:FREEFREETEST, A4:Mode 9: Freq.=3331.46					
	SC1:FREEFREETEST, A4:Mode 10: Freq.=3333.					

Figure 16: Validity Tests Percent Errors for Tie Rods

Steering Rack Mounting Plate

	Max Stress (psi)	Max Displacement (in)	FS
Actual Load Case	33400	0.000595	1.19760479
Unit Displacement Test	32800000	1	0.001219512
Dedicated Load Case	35700	0.272	1.120448179
Unit Temperature Test	0.000181	0.00672	220994475.1
Unit Gravity Test (X)	1.72	9.45E-08	23255.81395
Unit Gravity Test (Y)	19	0.0000157	2105.263158
Unit Gravity Test (Z)	1.57	0.000000117	25477.70701

Figure 17: Patran Stress, Deflection, and Factor of Safety (FS) Results for Mounting Plate

Unit Temp Hand Calcs			Lo (in)	5		
$\Delta L = \alpha L_o \Delta T$	ΔL (in)		(These are rough estimations for CTE and Lo)			
	0.00675				**% Error =**	0.44%
Dedicated Load Hand Calcs		(approximation as a cantilever beam)				
I = 1/12 (bh^3)	0.00140625	$\delta_{max} = \frac{PL^3}{3EI}$	0.296296296			
					% Error =	8.20%
Weight Hand Calcs						
W = V * specific weight	0.365625					
Patran Calculated Weight (ll	3.61E-01				**% Error =**	1.16%
Free Free Test Results	SC1:FREEFREE, A2:Mode 1: Freq.=0.000666953					
	SC1:FREEFREE, A2:Mode 2: Freq.=0.000714626					
	SC1:FREEFREE, A2:Mode 3: Freq.=0.000914605					
	SC1:FREEFREE, A2:Mode 4: Freq.=0.000991035					
	SC1:FREEFREE, A2:Mode 5: Freq.=0.00104871					
	SC1:FREEFREE, A2:Mode 6: Freq.=0.00159652					
	SC1:FREEFREE, A2:Mode 7: Freq.=777.723					
	SC1:FREEFREE, A2:Mode 8: Freq.=1143.33					
	SC1:FREEFREE, A2:Mode 9: Freq.=1439.65					
	SC1:FREEFREE, A2:Mode 10: Freq.=1998.66					

Figure 18: Validity Tests Percent Errors for Mounting Plate

Conclusion

When comparing the results of the validity checks to theoretical calculations, relatively small percent errors were found, proving the mathematical validity of the models. Under the expected operational load conditions, the larger steering support reported a Factor of Safety of 3.94, while the smaller option gave 1.08. In order to ensure the safety of the driver and the steering column itself, it is recommended that the design of the steering supports continue with the larger, ¾" SCH 40 option.

The tie rods reported acceptable Factors of Safety of 2.66 for both tension and compression, proving the current design is sufficient. In the future, students can look into optimizing the tie rods by using thinner steel or aluminum tubing in order to reduce the weight. For the steering rack mounting plate, a Factor of Safety of 1.20 was calculated. This test had the plate experience moments far larger than physically expected, but it may be prudent for future students to mount the current plate more securely or manufacture another plate of a stronger material. Either way, future weight optimization may be done by decreasing material on the corners of the plate, but this should first be tested using FEA.

This study was performed using estimated loads and idealized models. Going forward, students will want to perform physical tests with the manufactured steering components. Once the steering system is assembled and attached to the front suspension, students can test the tie rods by placing strain gauges along the length of each and taking measurements while steering the car. Repeating this test at different speeds will give more accurate results compared to the idealized models used in this paper. The steering supports can also be tested with strain gauges. Multiple drivers can apply lateral forces on the steering wheel when getting out of the car, giving more realistic load values for Finite Element models.

As the design of the vehicle develops in the future, it is important for students to revisit tests of this nature. Since the car is in its early design phase, the suspension and steering geometries are likely to change, with the steering system components likely to follow. Further tests can be performed on other components of the steering system, such as the steering column, U-joints, and hardware used to mount the steering components to the chassis. Weight optimization can also be done in order to enhance the performance of the car.

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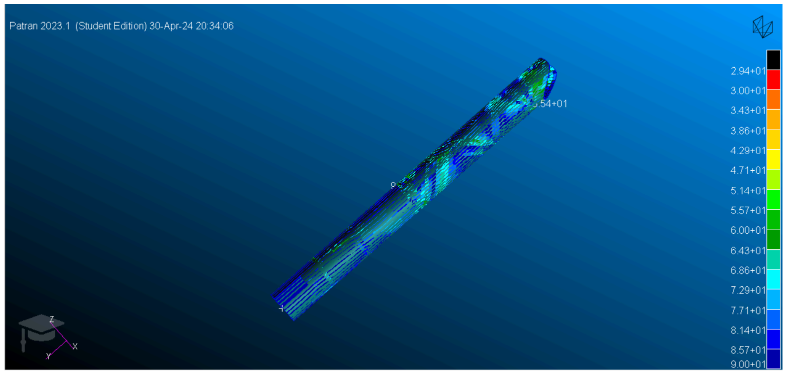
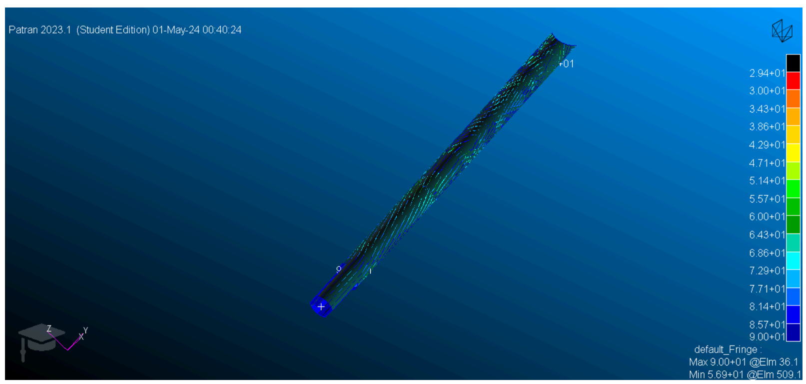
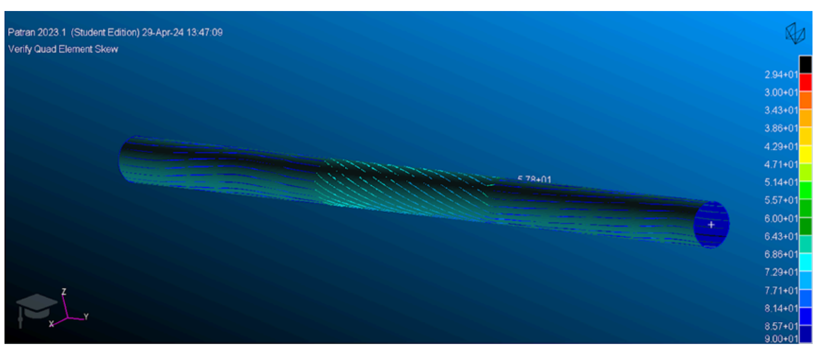
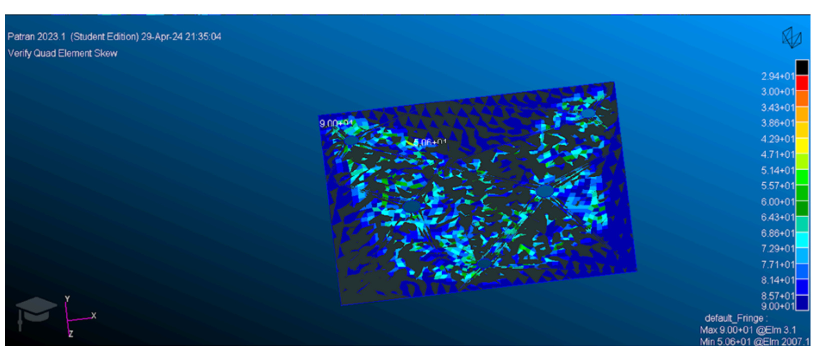
Appendix

A. Skew Tests to Verify Integrity of Created Meshes

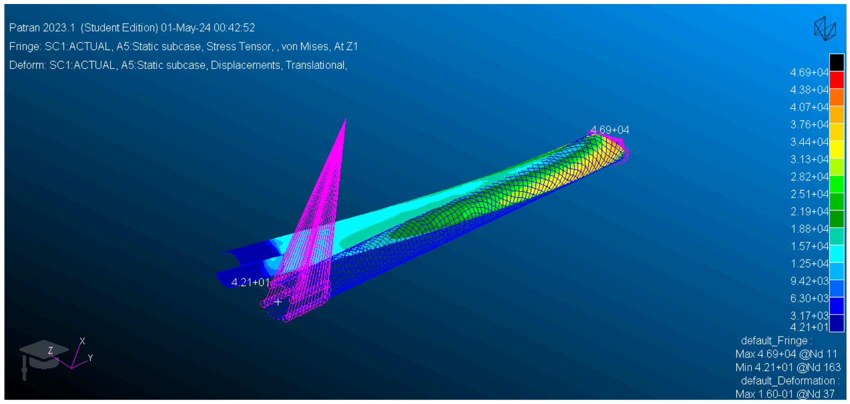


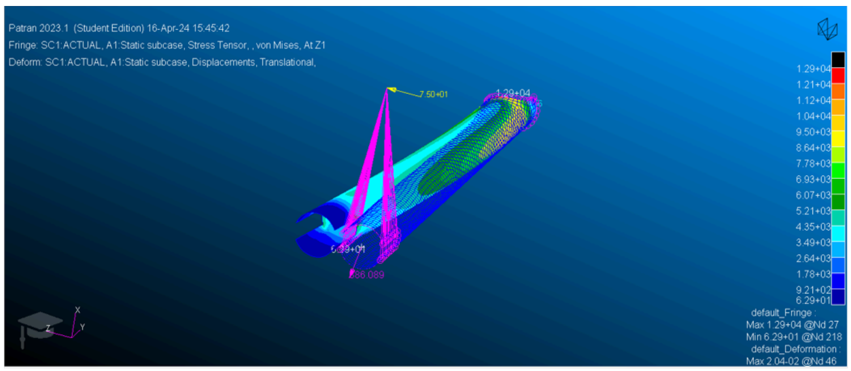


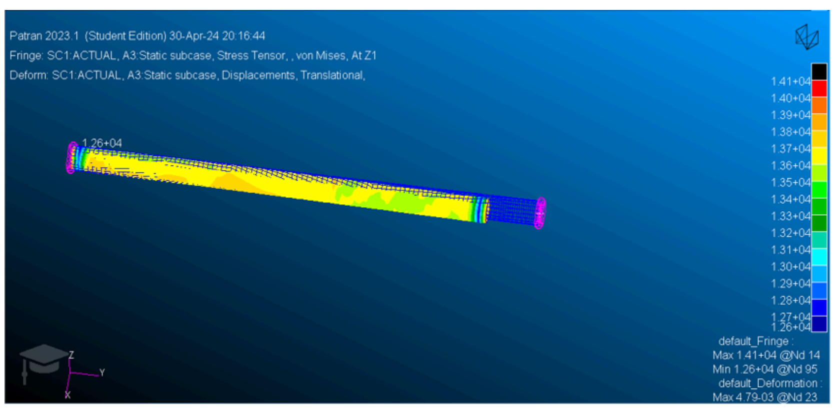


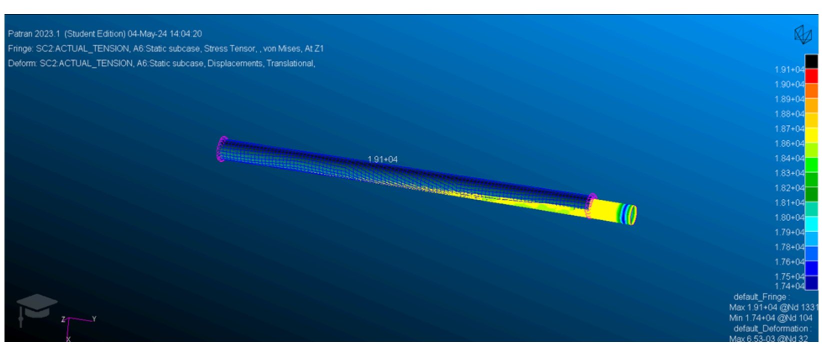


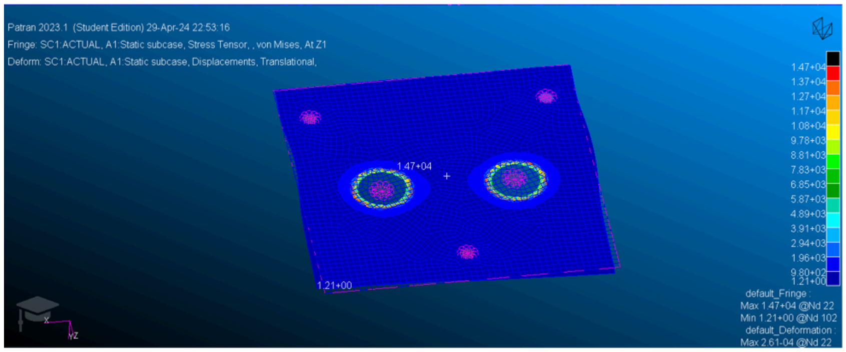
B. Stress Results of Operational Load Case










Patran 2023.1 (Student Edition) 29-Apr-24 22:53:16
Fringe: SC1:ACTUAL, A1:Static subcase, Stress Tensor, , von Mises, At Z1
Deform: SC1:ACTUAL, A1:Static subcase, Displacements, Translational,
1.47+04
1.21+00
1.47+04
1.37+04
1.27+04
1.17+04
1.08+04
9.78+03
8.81+03
7.83+03
6.85+03
5.87+03
4.89+03
3.91+03
2.94+03
1.96+03
9.80+02
1.21+00
default_Fringe :
Max 1.47+04 @Nd 22
Min 1.21+00 @Nd 102
default_Deformation :
Max 2.61-04 @Nd 22
X
YZ