Development of Cube Swarm for Search and Rescue Applications - Appendix B

Solidworks Finite Element Analysis (FEA

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Solidworks Finite Element Analysis (FEA)

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Parameters for FEA

All materials simulated as PLA with a Yield Strength of 35 MPA

While PLA's typical yield strength is between 60 and 75 MPA, PLA parts used for this project were 3D printed. Therefore, the PLA was melted down, thus changing properties. Additionally, infills of the parts varied in number of walls and infill density (15 Percent to 80 percent).

Gripper Assembly Component Analysis

Upper Arm FEA

Upper Arm Specific Parameters

The arm was fixed on about the cylinders on each end next to the geared portion of the arm. Value of the forces applied in the vertical direction at the end of each tooth is the total force distributed amongst the teeth. The same convention was used for the horizontal force value.

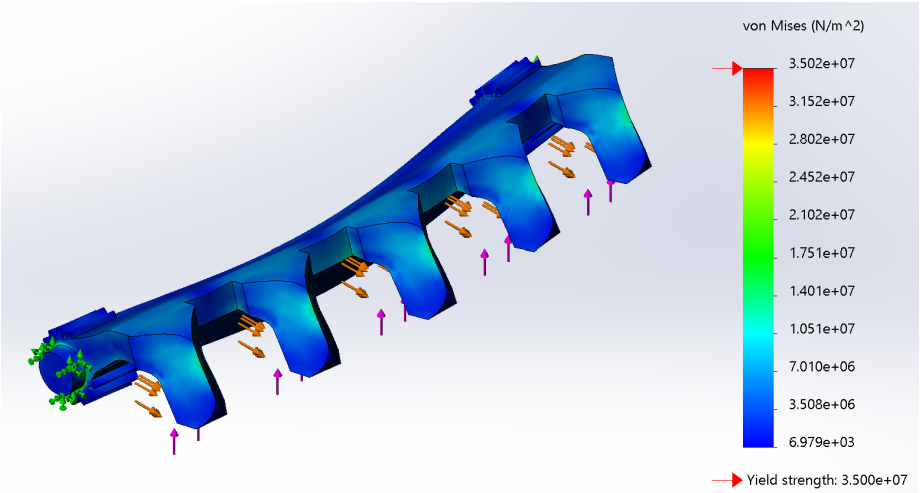


Figure 1: Top Arm Yield Strength
Horizontal and Vertical Force Applied to Teeth of Arm = 81N

Forces the Gripper Experiences Based on Static Calculations

Static calculations iterated the weight of the cube, for ALL forces from static calculations applied in FEA, assume one cubes mass = 850 grams.

TA = Total Vertical Force seen in FEA

TA2 = Total Horizontal Force seen in FEA

```
mass = 850
Solution:
FR_value = 19.2135
TA_value = 12.3307
TA2_value = 19.2574
BA_value = 3.9000
```

(a) 1 Cube Forces

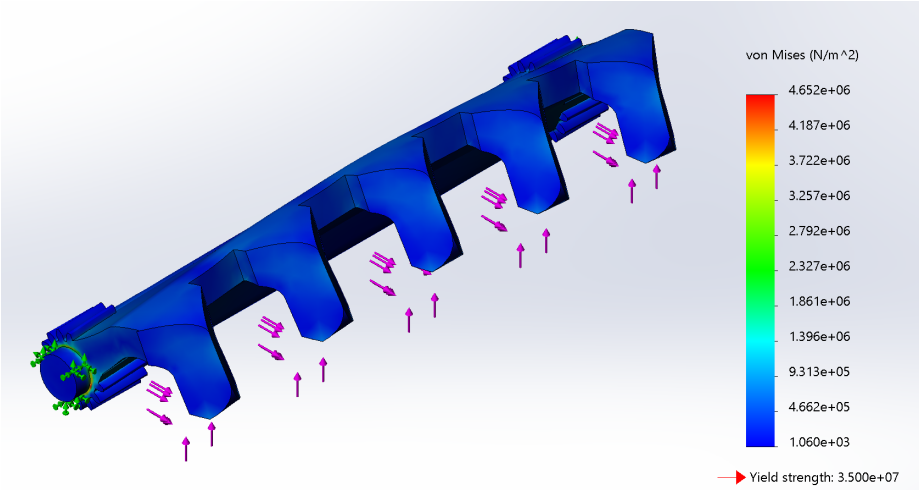
```
mass = 850
Solution:
FR_value = 56.5827
TA_value = 12.4298
TA2_value = 56.6271
BA_value = 3.8035
```

(b) 2 Cubes Forces

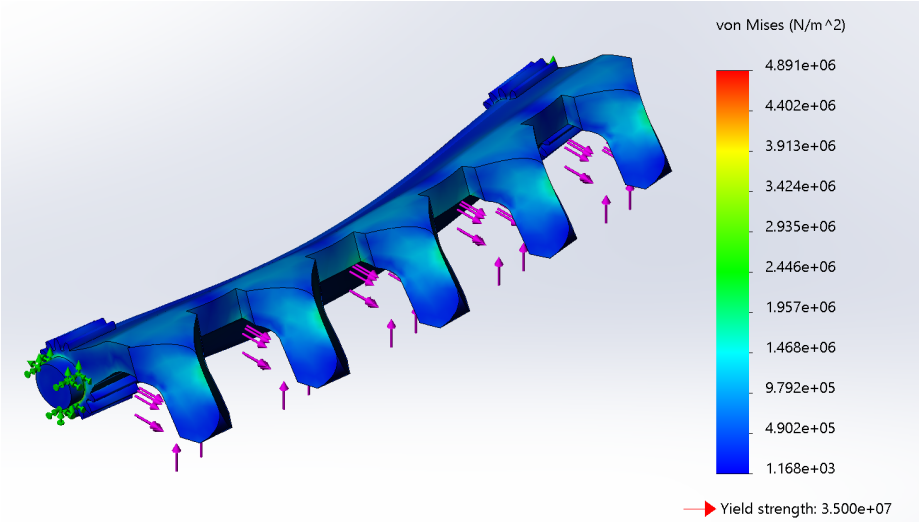
```
mass = 850
Solution:
FR_value = 119.6830
TA_value = 12.5973
TA2_value = 119.7283
BA_value = 3.6405
```

(c) 3 Cubes Forces

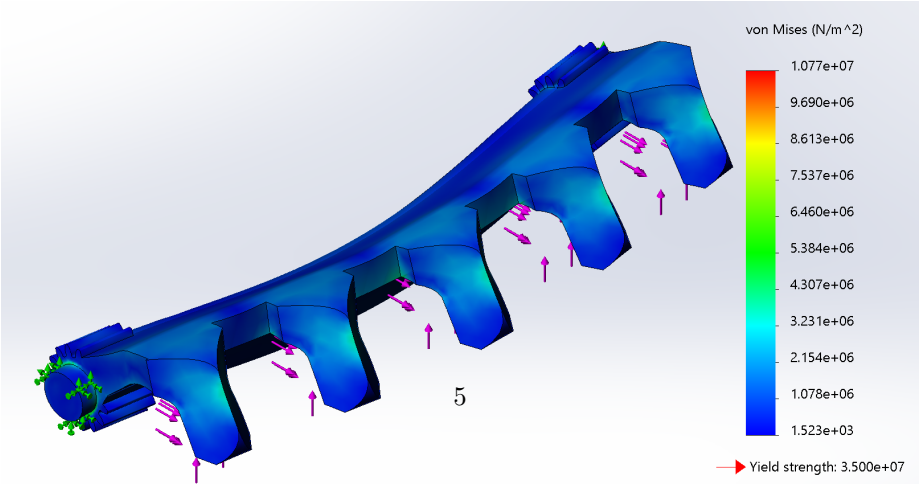
Figure 2



(a) 1 Cube Forces



(b) 2 Cubes Forces



(c) 3 Cubes Forces

Figure 3

Top Arm FEA Results Summary

The top arm is able to endure substantial force in the X and Y directions before reaching the maximum yield strength of 35MPA. Assuming that the top arm of the gripper assembly undergoes the forces seen in the static calculations the part will never exceed the yield strength set at 35MPA. Due to the location of forces and the design of the arm with teeth the areas that see higher stress are the bending points of where the teeth turn down.

Bottom Arm FEA

Bottom Arm Specific Parameters

The arm was fixed on about the cylinders on each end next to the geared portion of the arm. Value of the forces applied in the vertical direction at the end of each tooth is the total force distributed amongst the teeth.

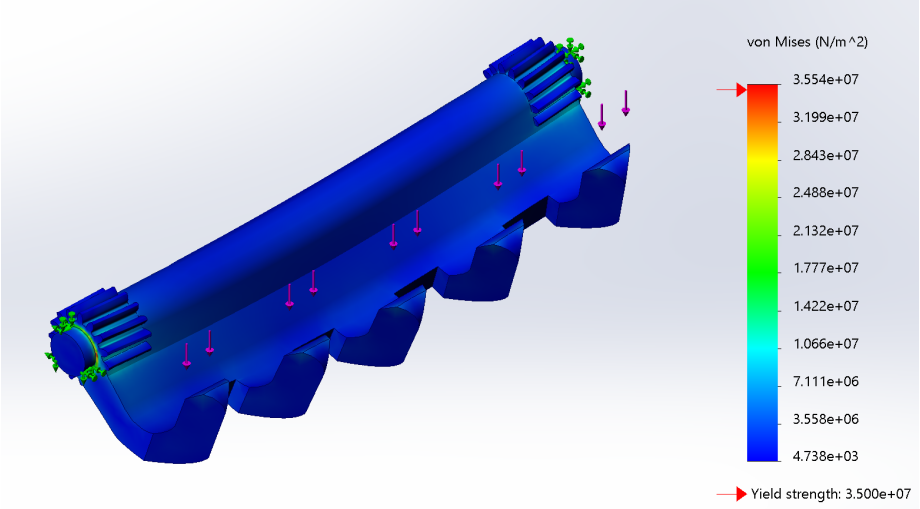


Figure 4: Bottom Arm Yield Strength
Vertical Force Applied to Teeth of Arm = 135N

Forces the Gripper Experiences Based on Static Calculations

Static calculations iterated the weight of the cube, for ALL forces from static calculations applied in FEA, assume one cubes mass = 850 grams.

BA = Total Horizontal Force seen in FEA

```
mass = 850
Solution:
FR_value = 19.2135
TA_value = 12.3307
TA2_value = 19.2574
BA_value = 3.9000
```

(a) 1 Cube Forces

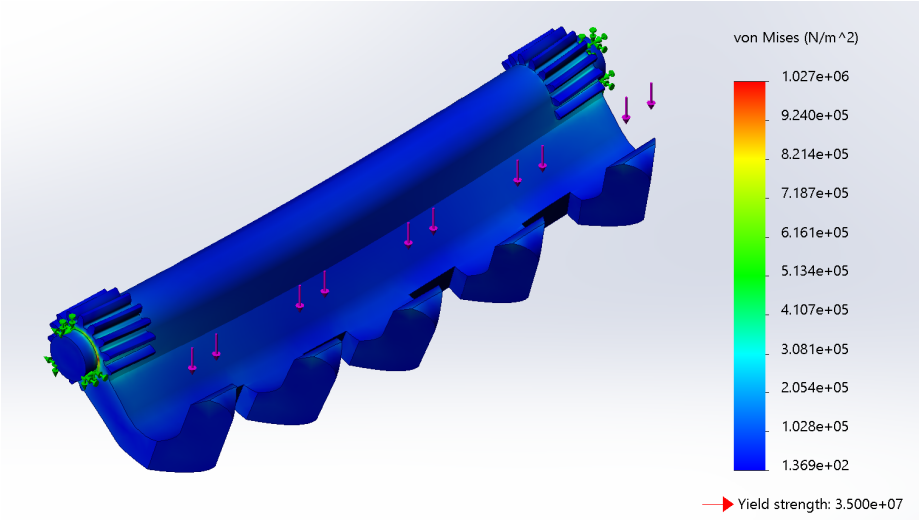
```
mass = 850
Solution:
FR_value = 56.5827
TA_value = 12.4298
TA2_value = 56.6271
BA_value = 3.8035
```

(b) 2 Cubes Forces

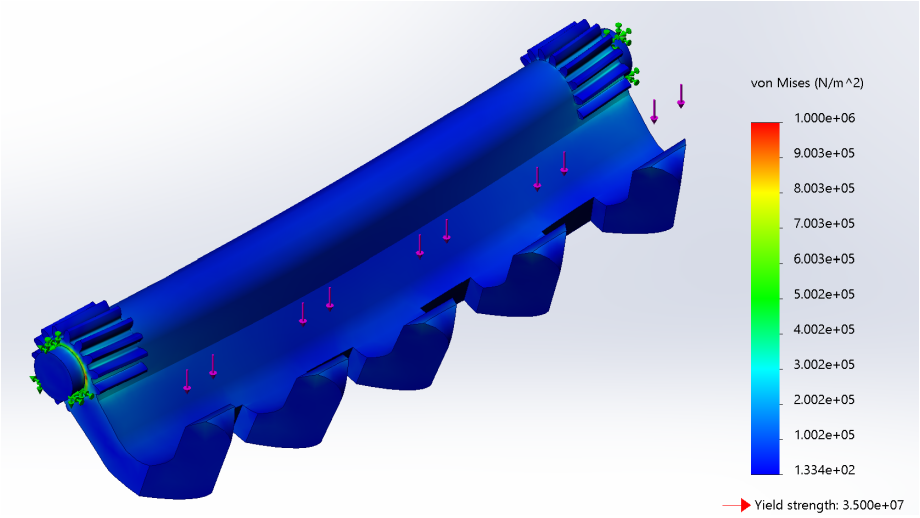
```
mass = 850
Solution:
FR_value = 119.6830
TA_value = 12.5973
TA2_value = 119.7283
BA_value = 3.6405
```

(c) 3 Cubes Forces

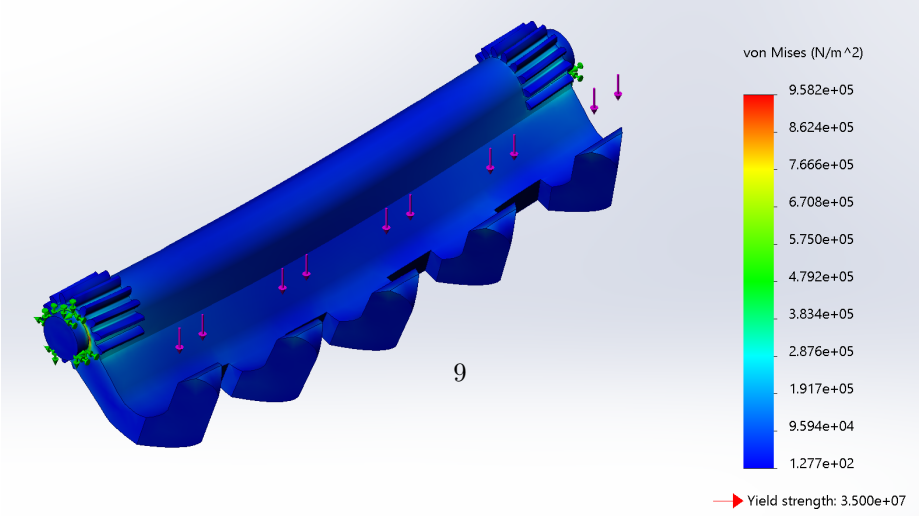
Figure 5



(a) 1 Cube Forces



(b) 2 Cubes Forces



(c) 3 Cubes Forces

Figure 6

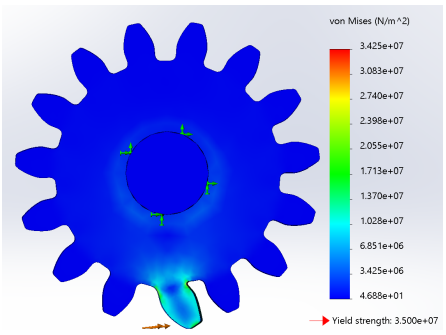
Bottom Arm FEA Results Summary

The bottom arm is able to endure substantial force in the Y direction before reaching the maximum yield strength of 35MPA. Because the bottom arm only experiences forces from 1 direction it is able to withstand a greater one beore reaching the yield. Assuming that the bottom arm of the gripper assembly undergoes the forces seen in the static calculations the part will never exceed the yield strength set at 35MPA. Due to the location of force and the design of the arm the areas of high stress are at the pins that hold the arm in the assembly and at the base of the gears teeth on each side.

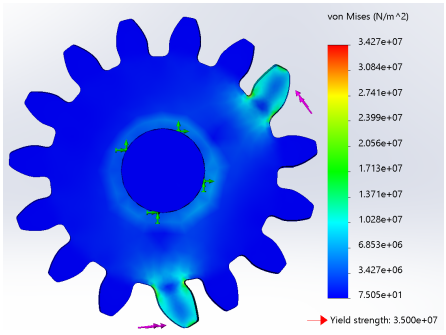
Transfer Gear FEA

Transfer Gear Specific Parameters

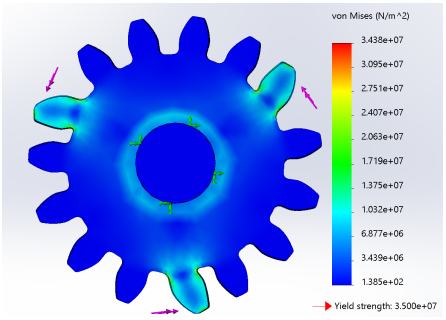
The gear was fixed on about the extruded cylinder on the front face, and the shelled cylinder on the back face. geared portion of the arm. While the gears physically contact at each gears pitch circle, the forces were applied at the end of the teeth to simulate a "worst case" scenario.



(a) 1 Force Yield of Part



(b) 2 Force Yield of Part



(c) 3 Force Yield of Part

Figure 7: Each force in each figure equaled 43.5N

The max yield stress occurred along the base of the tooth

Forces the Gear Experiences Based on Static Calculations

Static calculations iterated the weight of the cube, for ALL forces from static calculations applied in FEA, assume one cubes mass = 850 grams. The forces the gear experiences are identical for any number of cubes. The interfacing geometry relieves any load from transmitting through the gear train and onto the servo motors.

fT1 = Force between top transfer gear (spur gear 1) and top gripper arm

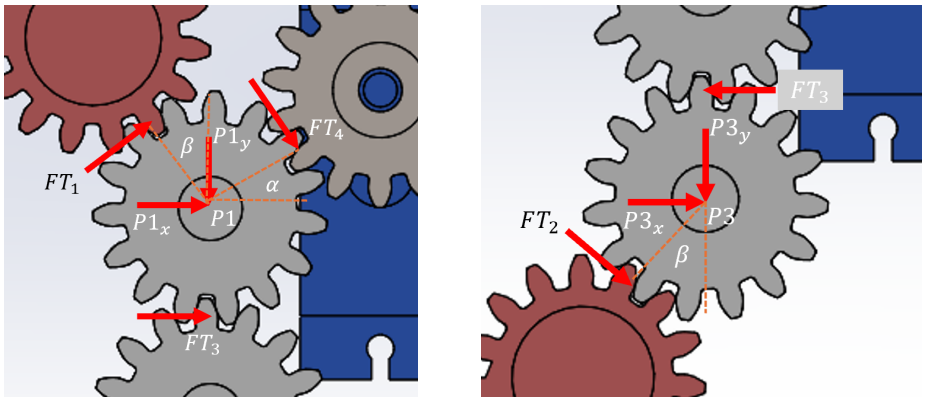
fT2 = Force between bottom transfer gear (spur gear 2) and bottom gripper arm

fT3 = Force between spur gear 1 and spur gear 2

fT4 = Force between spur gear 1 and servo motor gear

```
mass = 850
Solution:
fT1_value = -41.6001
fT2_value = -12.8421
fT3_value = 13.5180
fT4_value = 55.1181
```

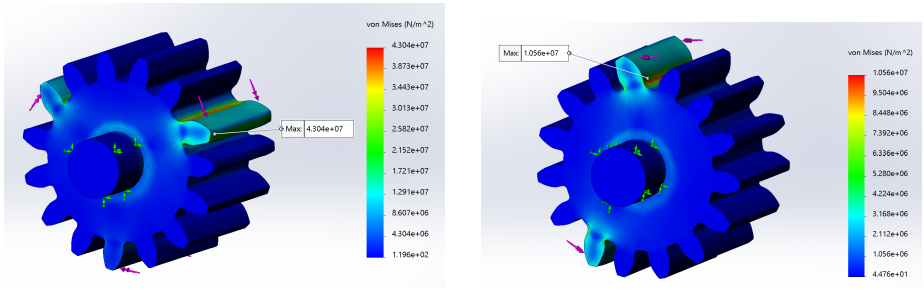
Figure 8: Static Calculation Forces on Gears



(a) Spur Gear 1 Force FBD

(b) Spur Gear 2 Force FBD

Figure 9: Reference Locations of Forces from Static Calculation FBD's



(a) Spur Gear 1

(b) Spur Gear 2

Figure 10: FEA on Spur Gears based on Static Calculation Forces

Spur Gear 1 FEA Results Summary

Spur Gear 1 meshes with three different entities and therefore experiences three forces of various magnitude. Having all three forces applied to the gear in Solidworks FEA did result in a max stress of 43MPA, which is above the 35MPA max yield stress that was set. While noticing that the forces can exceed the parts yield, there are many factors at play for this part that may make this parts max yield strength greater than 35MPA such as infill density and the forces acting at the pitch circle and not the end of the teeth for example. The max stress occurred along the base of the tooth.

Spur Gear 2 FEA Results Summary

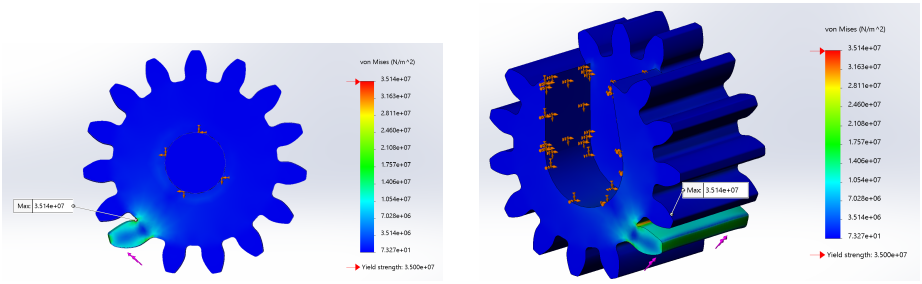
Spur Gear 2 meshes with two different entities and therefore experiences two forces of various magnitude. Having all three forces applied to the gear did not

exceed the 35MPA max yield stress that was set. The max stress occurred along the base of the tooth

Servo Motor Gear FEA

Servo Motor Gear Specific Parameters

The gear was fixed on about the extruded cylinder on the front face, and the shelled slot for the servo motor horn on the back face. While the gears physically contact at each gears pitch circle, the forces were applied at the end of the teeth to simulate a "worst case" scenario.



(a) Servo Motor Gear Part Yield FEA 1 (b) Servo Motor Gear Part Yield FEA 2

Figure 11: FEA on Servo Gear until Part reaches Maximum Yield Strength

Force Applied to Gear Tooth = 44.5N

Forces the Gear Experiences Based on Static Calculations

Static calculations iterated the weight of the cube, for ALL forces from static calculations applied in FEA, assume one cubes mass = 850 grams. The forces the gear experiences are identical for any number of cubes. The interfacing geometry relieves any load from transmitting through the gear train and onto the servo motors.

fT1 = Force between top transfer gear (spur gear 1) and top gripper arm

fT2 = Force between bottom transfer gear (spur gear 2) and bottom gripper arm

fT3 = Force between spur gear 1 and spur gear 2

fT4 = Force between spur gear 1 and servo motor gear

```
mass = 850
Solution:
fT1_value = -41.6001
fT2_value = -12.8421
fT3_value = 13.5180
fT4_value = 55.1181
```

Figure 12: Static Calculation Forces on Gears

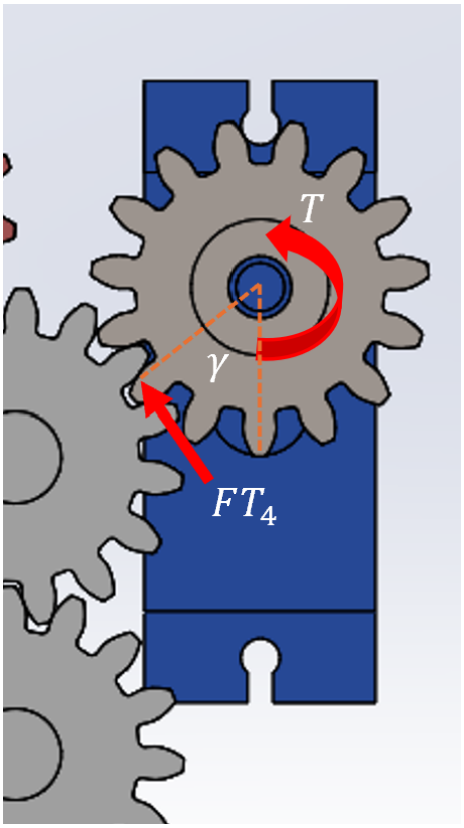
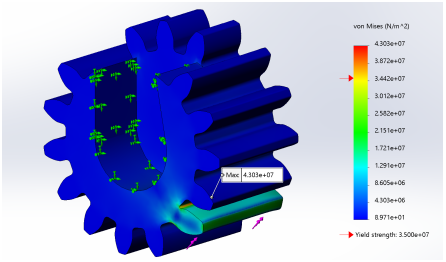
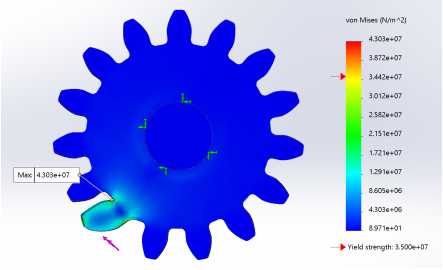


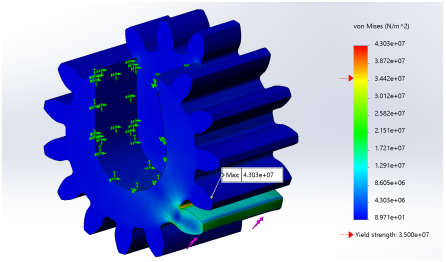
Figure 13: Reference Locations of Forces from Static Calculation FBD's



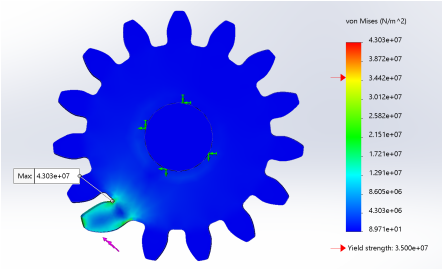
(a) Servo Motor Gear Image 1: 1 Force FEA



(b) Servo Motor Gear Image 2: 1 Force FEA



(c) Servo Motor Gear Image 3: Force + Torque



(d) Servo Motor Gear Image 4: Force + Torque

Figure 14: FEA on Servo Motor Gears based on Static Calculation Forces

Servo Motor Gear FEA Results Summary

Like the spur gears, the forces the servo gear experiences from the servo motor specs and loads the gear will experience a max stress greater than 35MPA. While noticing that the forces can exceed the parts yield, there are many factors at play for this part that may make this parts max yield strength greater than 35MPA such as infill density and the forces acting at the pitch circle and not the end of the teeth for example. Other factors include that this gear has a large slot in it for the servo horn, which could be affecting structural integrity. However, because the max stress seen is comparable to the spur gears this is unlikely. The max stress occurred along the base of the tooth just like the spur gears.

Receiver Analysis

Receiver FEA

Receiver Specific Parameters

The receiver was fixed about three screw holes on each side of the receiver. All forces seen are applied the whole face/plane, not singular points or lines like in the static calculations.

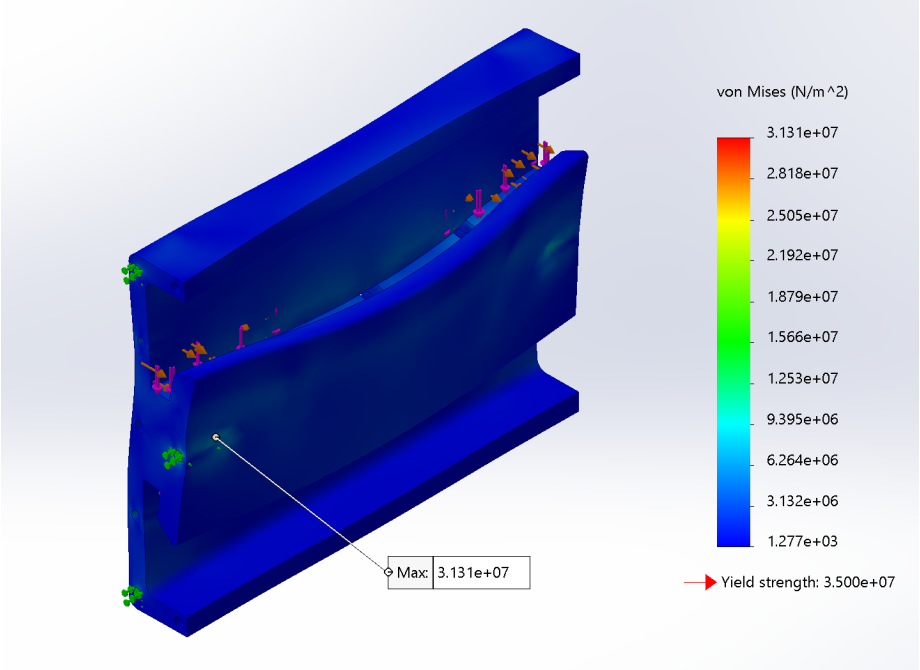


Figure 15: Receiver Yield Strength
Each Force applied to a face = 1000N

While 1000N for each force did not make the part reach its yield, it is clear the part can withstand a substantial amount of force before breaking. Even if the part is simulated as solid PLA instead of 15 to 40 percent infill.

Forces on the Receiver Based on Static Calculations

Static calculations iterated the weight of the cube, for ALL forces from static calculations applied in FEA, assume one cubes mass = 850 grams. The forces below are as if the they were being applied to the gripper in the static calculations. However, these same values can be used as if they were acting in the opposite direction to apply in the appropriate and corresponding areas.

TA = Total Vertical Force in Negative Direction seen in FEA

TA2 = Total Horizontal Force seen in FEA

BA = Total Vertical Force seen in FEA Applied in the positive direction

```
mass = 850
Solution:
FR_value = 19.2135
TA_value = 12.3307
TA2_value = 19.2574
BA_value = 3.9000
```

(a) 1 Cube Forces

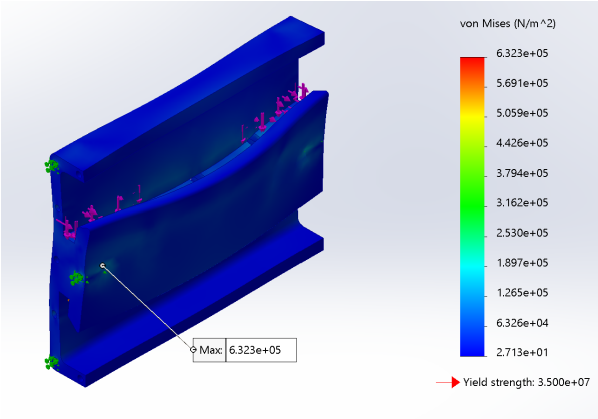
```
mass = 850
Solution:
FR_value = 56.5827
TA_value = 12.4298
TA2_value = 56.6271
BA_value = 3.8035
```

(b) 2 Cubes Forces

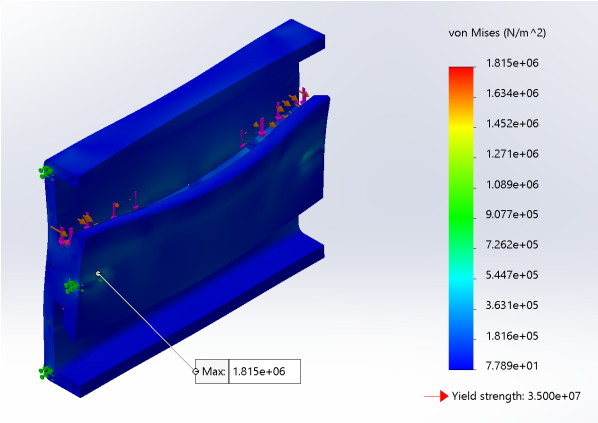
```
mass = 850
Solution:
FR_value = 119.6830
TA_value = 12.5973
TA2_value = 119.7283
BA_value = 3.6405
```

(c) 3 Cubes Forces

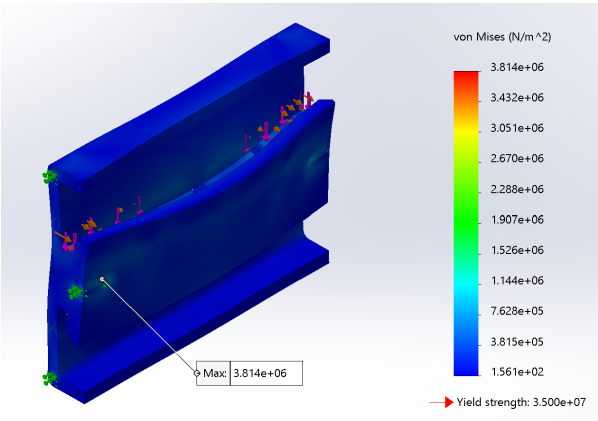
Figure 16



(a) 1 Cube Forces



(b) 2 Cubes Forces



(c) 3 Cubes Forces

Figure 17

Receiver FEA Results Summary

The receiver is very sturdy and will not exceed the maximum yield stress of 35 MPA with three cubes connected and overhanging. As can be seen from the FEA for the Yield strength of the part, it can theoretically experience 1000N forces applied to various faces before reaching max yield stress. While those values are unreasonable given the 20 percent infill construction and only three walls for the 3d print, the FEA shows sustained strength for the design.

Full Cube Analysis

Full Cube FEA

Full Cube Specific Parameters

For the full cube FEA, the forces that the gripper and frame of the robot experience were applied. Bolts were applied to necessary holes to keep everything "assembled." The cube was fixed about the frames top as we felt it would have the lease impact on how the forces and loads were distributed during simulation. All parts in the assembly were PLA except the frame side plates, which were laser cut wood and simulated as Balsa.

Forces On the Gripper and Cube Frame

Static calculations iterated the weight of the cube, for ALL forces from static calculations applied in FEA, assume one cubes mass = 850 grams.

FR = Total Horizontal Force seen in FEA on the bottom point of the frame

TA = Total Vertical Force in Positive Direction seen in FEA on Top Arm

TA2 = Total Horizontal Force seen in FEA on Top Arm

BA = Total Vertical Force in Negative Direction seen in FEA on Bottom Arm

```
mass = 850
Solution:
FR_value = 19.2135
TA_value = 12.3307
TA2_value = 19.2574
BA_value = 3.9000
```

(a) 1 Cube Forces

```
mass = 850
Solution:
FR_value = 56.5827
TA_value = 12.4298
TA2_value = 56.6271
BA_value = 3.8035
```

(b) 2 Cubes Forces

```
mass = 850
Solution:
FR_value = 119.6830
TA_value = 12.5973
TA2_value = 119.7283
BA_value = 3.6405
```

(c) 3 Cubes Forces

Figure 18

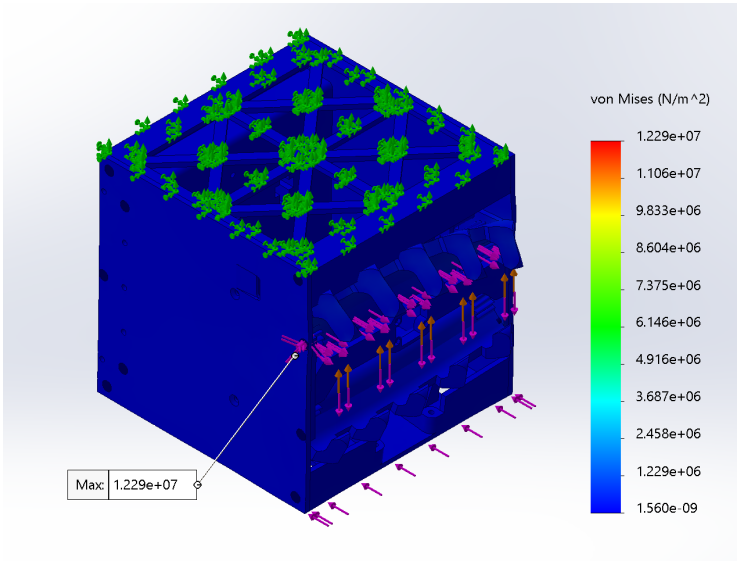


Figure 19: 1 Cube Forces

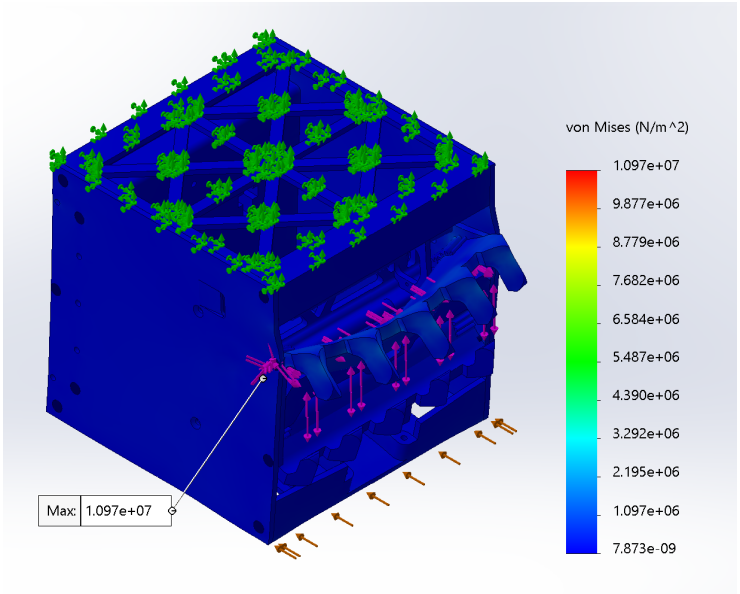


Figure 20: 2 Cube Forces

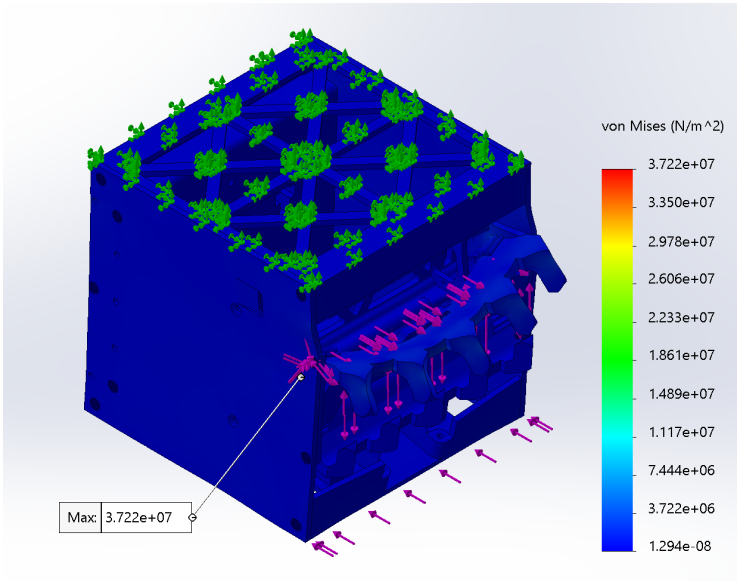


Figure 21: 3 Cube Forces

Full Cube FEA Results Summary

The big takeaway with the full cube assembly and all the various components within is the servo motors are under powered to firmly clamp and grip onto 3 cubes worth of weight. the constraint of the motors forced the design to not be solely reliant on the motors, but the weight of the cubes still puts stress on the parts in the system.

From the diagrams, by the time the weight of 3 cubes is being held up, the max yield stress of 35MPA is exceeded by 2MPA. The max stress is seen inside the gripper assembly where the top arm gear interacts with spur gear 1. The max stress being exceeded was not concerning because there will always by more than than one cube to support the three overhanging cubes.