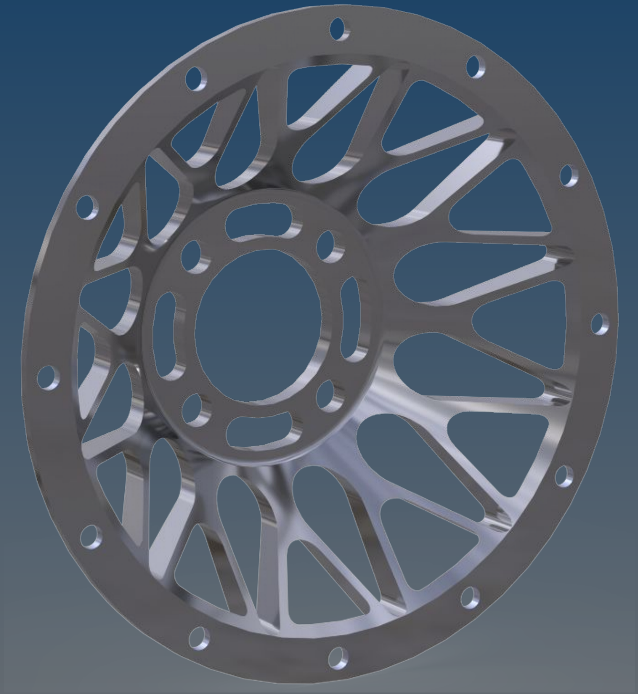
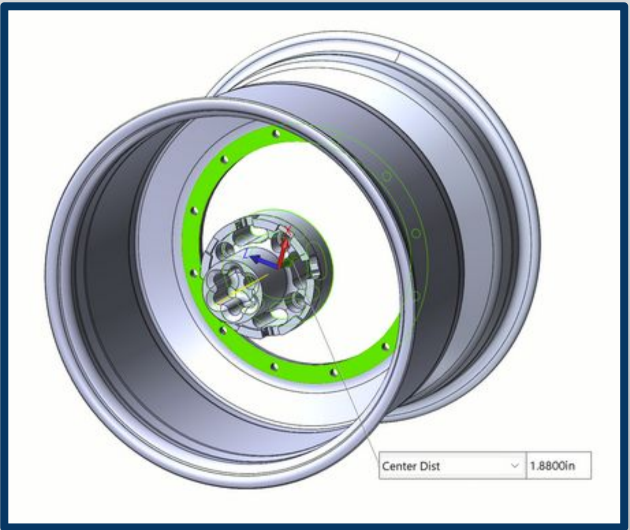
BFR 2024 Drivetrain Project



Gautham Jey

Design Scenario

- Wheel Center between hub and rim
- 12x ¼-20 bolt holes at 3.375" (rims)
- 4x ⅜-24 bolt holes at 1.2" (hubs)
- 1.88" offset between the hub face and rim face
- 1.75" diameter through hole centered on the face that interacts with wheel hub
- Minimize weight and maximize stiffness
- Loading: (10/8 Numbers)
  - Torque(X): 2.2 G / 4 * Torque Arm (4 brakes)- 549.3lbf-in
  - Axial (Y): 1.75 G / 2 (two-wheeling) - 364.5 lbf
  - Z Loading (Z): 1.6 G / 2 (two-wheeling) - 799 lbf



Design Targets

- Manufacturability
    - Easy-to-manufacture material
    - Can be done without specialized tooling
        - Ex: Lathe, Mill, and CNC versions
- Cost
    - Relatively cheap material
    - Doesn’t rely on specialized tooling
        - Ex: no 5-axis
- Reliability
    - Hesitant on composites until further research and IRL testing

Material Choice

- High specific strength and high stiffness/modulus
- Inexpensive
- Ease of manufacturing

Material	Composites (CF Toray T1100G)	Maraging Steel	Titanium Alloy (Beta C)	Al Alloy (7075-T6)
Specific Strength	3,911	298.78	260	204

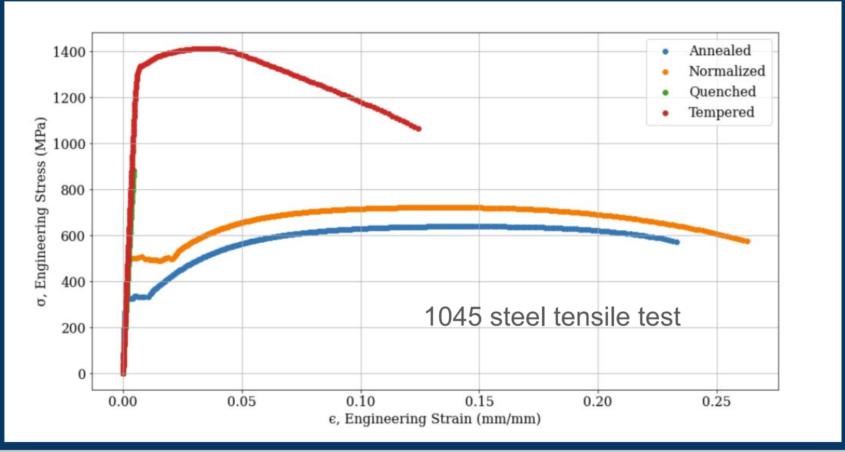
https://en.wikipedia.org/wiki/Specific_strength

Material Choice

- Metals: easy to manufacture (project focus)
- Titanium: expensive and difficult to machine
- Steel Vs Aluminum: steel is good for volume constraints, but we have a bigger mass constraint
    - ~½ the strength-weight ratio of alumiums
- **Design Targets: Aluminum is the best choice**

Aluminum

- Manufacturing Method: Wrought Vs Cast
  - Cast: cheaper but more defects and lower strength
  - **Wrought: mechanically formed after casting (less defects and stronger)**
- Alloys
  - 7000 series (Zinc)
    - Zinc alloy, used in aerospace
  - 6000 series (Magnesium and Silicon)
    - general purpose, **easy to machine**
- Common: 7075 Vs 6061
  - 7075 greater stiffness/strength (204 vs 115 kNm/kg)
  - 6061 is **~25% cheaper + machinability**
- Heat Treatments
  - Tempering increases yield strength
  - And elastic regime
- **Design Targets: 6061 T6**



6061 Aluminum

- Known as the all-purpose aluminum grade, most commonly used aluminum alloy for CNC machined parts.
- Yield Strength of ~276 MPa (~40000 psi).
- Brinell hardness of 95.
- Elasticity of 68.9 GPa (10000 ksi).
- Melting point range of 582°-652°C (1080°-1205°F)

7075 Aluminum

- One of the strongest aluminum alloys with strengths comparable to many steels.
- Yield Strength of ~503 MPa (~73000 psi).
- Brinell hardness of 150.
- Elasticity of 71.7 GPa (10400 ksi).
- Melting point range of 477°-635°C (890°-1175°F)

https://parts-badger.com/6061-vs-7075-aluminum/

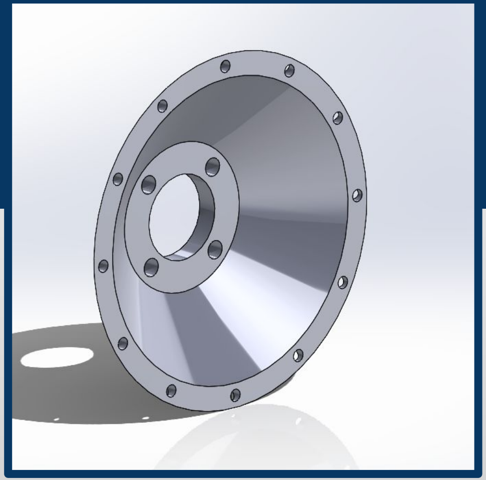
Research And Design Approach

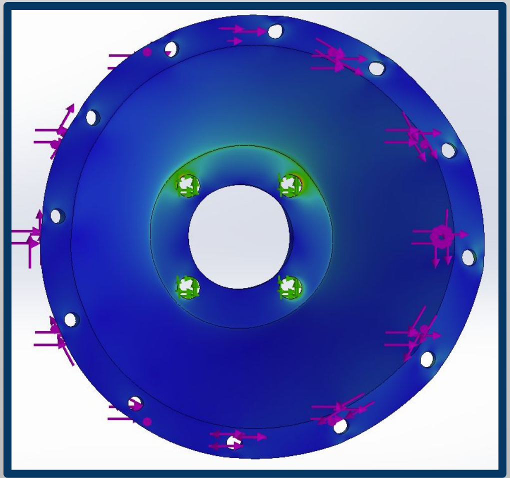
- Spoke-Like Design
- Remove material between holes
- Add material close to holes
- Can think of mapping material from each hub hole to each rim hole (Complete Graph)
- Adding each mapping might be excessive, only keeping some
- Think about manufacturability

https://keizerwheels.com/product/cl10-center-lock-fsae/

Baseline

- General volume of material
- Baseline mass: 1.43 lbs
- High stress by holes
- Stress concentrations when geometry suddenly changes
- Cone part is excessive and can be cut down to spoke style
- Need to consider adding fillets/curves to smooth transitions

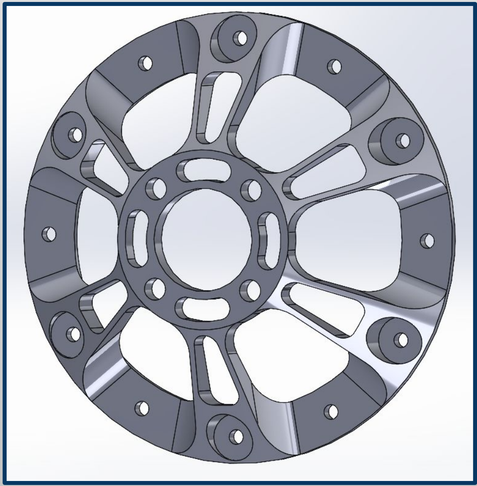


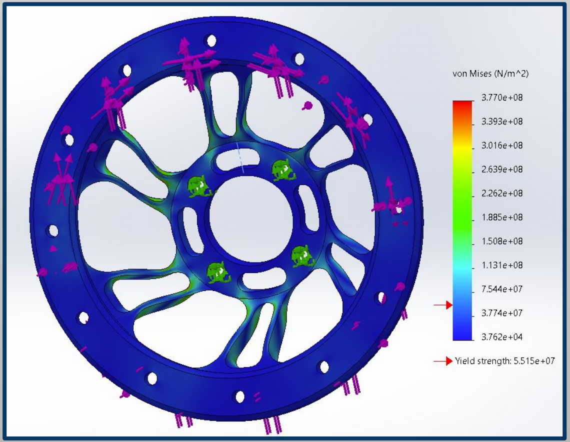


Scaling irrelevant since different material and old load case

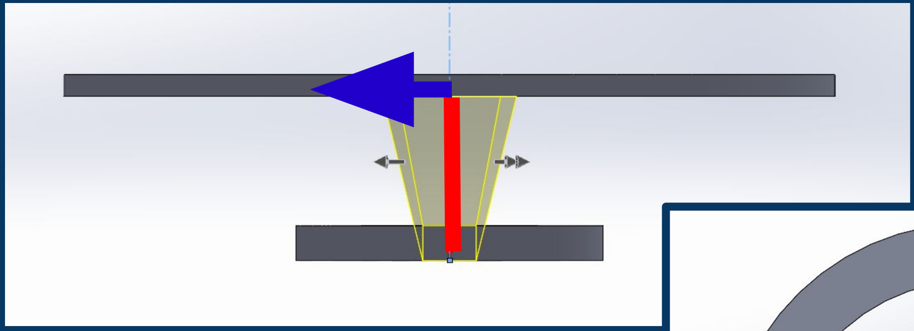
Iterations

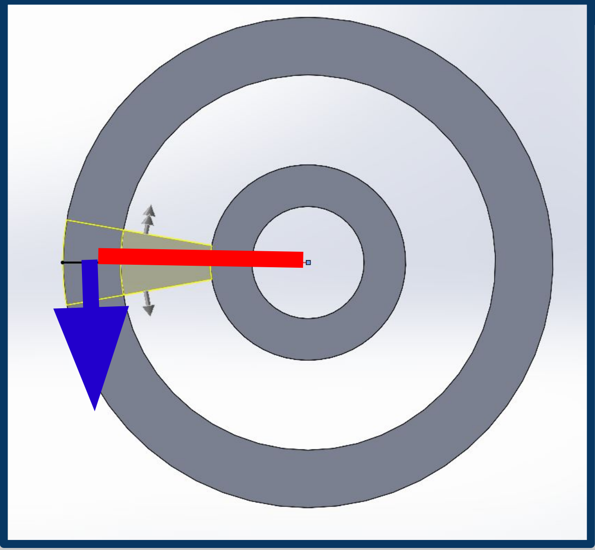
- Made revolved spokes at 6/12 holes (tried to reduce spokes for weight)
- Set arbitrary thicknesses and fillet diameters (didn't quantify and reason decisions)
- Didn't look at heat treatments
- High stress at spokes
- Decided to understand how loading impacted spokes





Iterations



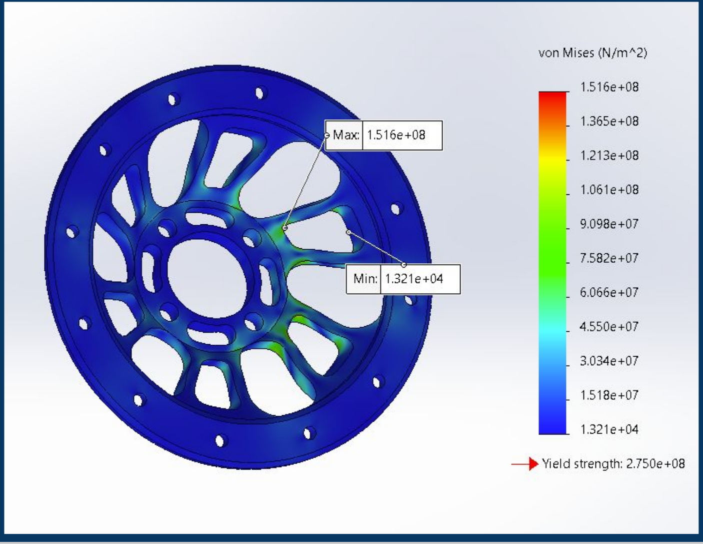


- From deformation plot, lot of movement from torque and/or z loading
- On each spoke, we view it as a bending problem. There is a component of bending about y and a component about x
- Two options to improve structure
  - Decrease moment arms
    - Will decrease applied moments on spoke
    - Not really possible due to constraints
  - Increase moment of inertias
    - Can make the spoke wider greatly increasing Iy and Ix
    - Can make spokes thicker
    - Can also remove area reduction of spoke and keep it straight

Torsion	$\phi = \frac{T L_0}{G J}$	$\tau = \frac{T \rho}{J}$	$\gamma = \frac{\phi \rho}{L_0}$
Stiffness and Flexibility	$k_{\text{axial}} = \frac{E A}{L_0} = \frac{1}{f_{\text{axial}}}$		$k_{\text{torsion}} = \frac{G J}{L_0} = \frac{1}{f_{\text{torsion}}}$
Bending	$\sigma = \frac{M c}{I}$		

Iterations

- Few iterations later of increasing spoke width and adjusting thickness + heat treatment, got acceptable solution
- Min FOS: 1.8
- Mass: 1.15 lbs
- Didn’t like that revolved spokes decreased in width
- Wanted to quantify parameters

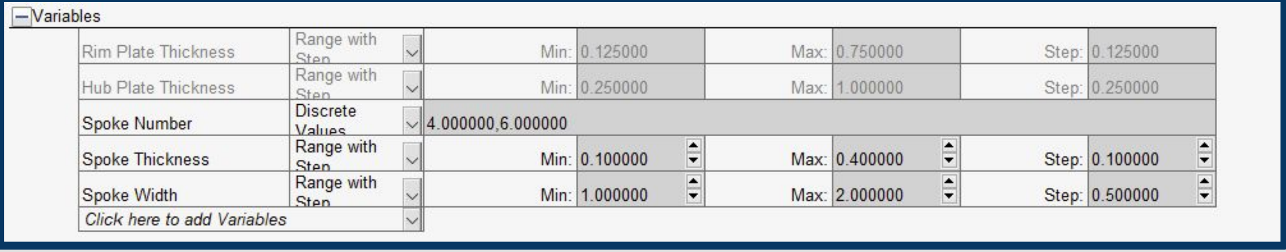


Property	Value	Units
Elastic Modulus	10007603.9	psi
Poisson's Ratio	0.33	N/A
Shear Modulus	3770981.179	psi
Mass Density	0.0975436609	lb/in^3
Tensile Strength	17996.86264	psi
Compressive Strength		psi
Yield Strength	7998.613676	psi
Thermal Expansion Coefficient	1.333333333e-05	/°F
Thermal Conductivity	0.00227371	Btu/(in·sec·°F)
Specific Heat	0.3105	Btu/(lb·°F)
Material Damping Ratio		N/A

Property	Value	Units
Elastic Modulus	10007604	psi
Poisson's Ratio	0.33	N/A
Shear Modulus	3770981.198	psi
Mass Density	0.0975436609	lb/in^3
Tensile Strength	44961.69898	psi
Compressive Strength		psi
Yield Strength	39885.37799	psi
Thermal Expansion Coefficient	1.333333333e-05	/°F
Thermal Conductivity	0.00223225	Btu/(in·sec·°F)
Specific Heat	0.214006	Btu/(lb·°F)
Material Damping Ratio		N/A

6061 no heat treatment VS T6

Optimization



Variables

Rim Plate Thickness	Range with Step	Min: 0.125000	Max: 0.750000	Step: 0.125000
Hub Plate Thickness	Range with Step	Min: 0.250000	Max: 1.000000	Step: 0.250000
Spoke Number	Discrete Values	4.000000,6.000000		
Spoke Thickness	Range with Step	Min: 0.100000	Max: 0.400000	Step: 0.100000
Spoke Width	Range with Step	Min: 1.000000	Max: 2.000000	Step: 0.500000
Click here to add Variables				

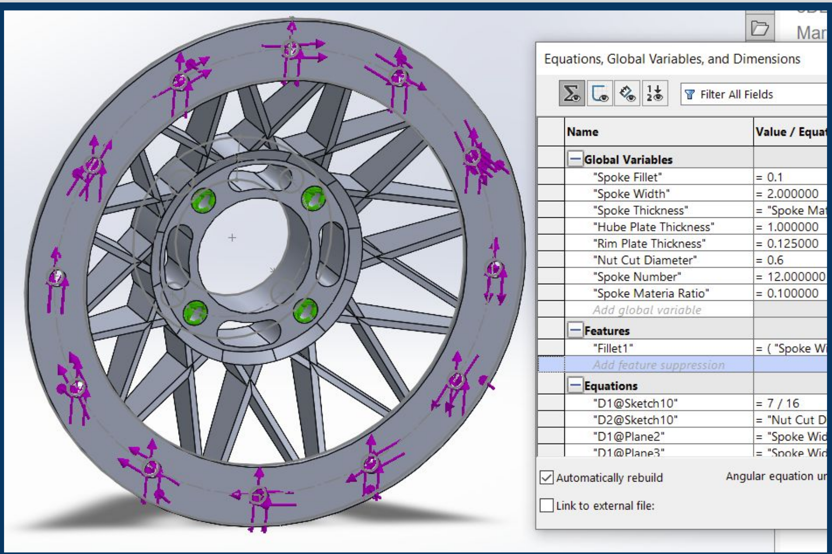
- Design Study
  - Can parameterize model, set a range of values for each parameters, set strength constraints, and set goal to minimize mass
- To optimize, we have two way of doing it
  - Design Study
    - Slow Setting: set step values for parameters and simulate every iteration (10^2 - 10^3)
      - Takes too much time and computation
    - Fast Setting: SolidWorks chooses few iterations (10^1) to simulate
      - If dynamically, this could converge to an optimal solution
      - If randomly select, not as useful
  - DOE + Design Study
    - Simulate edge cases and interpolate with DOE
    - Identify significant terms
    - Simulate again
      - Adjust the range of values and step sizes for parameters depending on how significant
- https://docs.google.com/spreadsheets/d/1SMT5XEg40nVRpHcWgympEDq8oVh474Yb4IMTR7zO-PY/edit?usp=sharing

Iterations

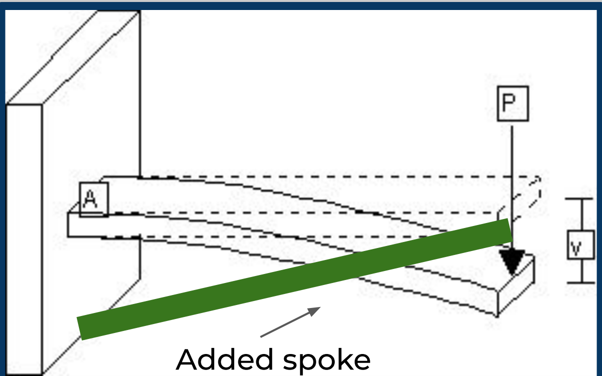
Variables	low (in)	high (in)
1. Spoke Width	0.5	2
1. Spoke Material Ratio	0.1	0.75
3. Spoke Count	4	12
4. Rim Plate Thickness	0.125	0.75
5. Hub Plate Thickness	0.125	1

Bounds chosen to be within reason, if DOE favored an extrema, can examine going past it

- Couldn’t fully get the Design Study to work, but tested few variations
- Realizations:
  - Can decrease thickness of rim plate and hub plate for significant mass saving
  - Higher spoke count, thinner, wide spacing proved to be mass efficient
  - Intuition: greater distribution of support; due to crossover of spokes, had diagonal members preventing bending



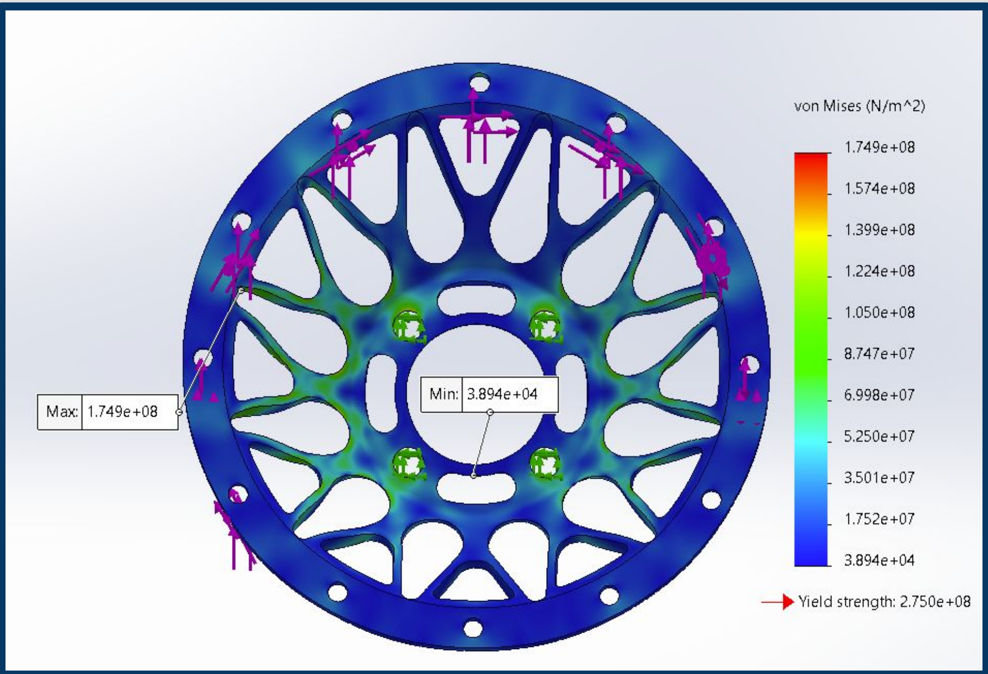
(Mass of Example Iteration: 0.98lbs)

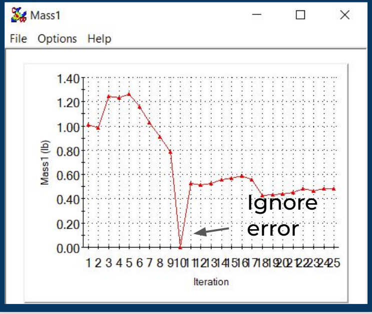


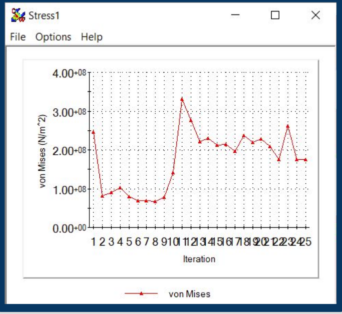
Final Iteration - 20+ revisions

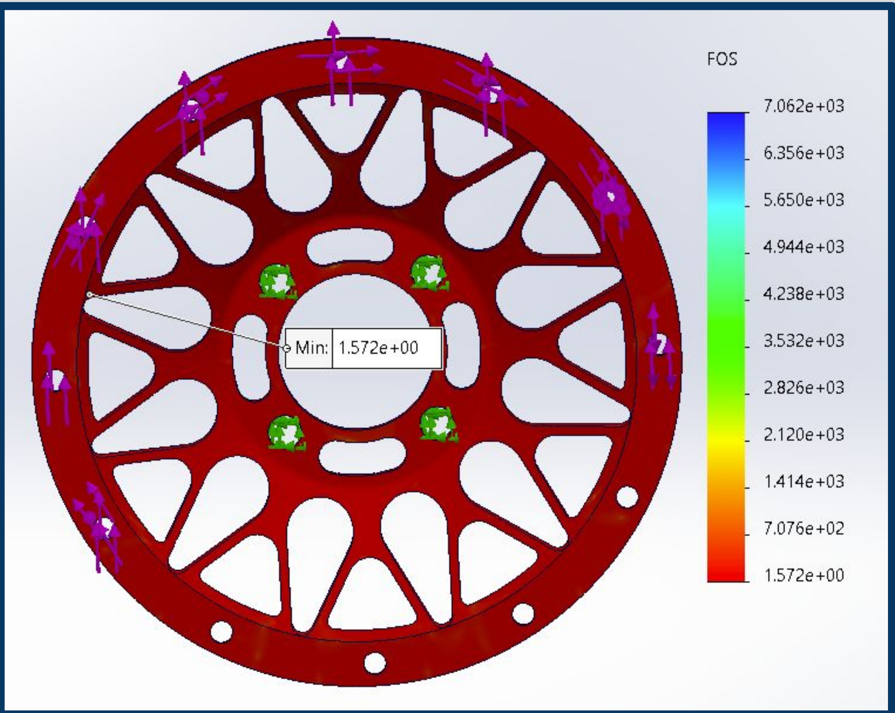
- 12 sets of spokes, 0.1 material ratio, 2 in width between pair of parallel spokes
- Hub Plate Thickness: 0.25 in
- Rim Plate Thickness: 0.125 in
- Material added near the hub (low polar moment of area and avoiding stress concentration)
- Fillets refined by minimizing, hitting a high stress, then adding material until no longer limiting factor
- Fillet added between hub plate and spokes to remove stress concentration
- **Min FOS: 1.5, Mass: 0.43 lbs**

Plots









- **Max Displacement = 0.45mm**

Manufacturability

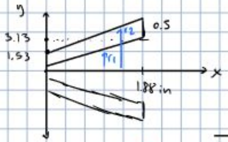
- Start with round stock
- Lathe or CNC Lathe to volume
- CNC Mill with two orientations
  - Hub side secured to vice
  - Rim side secured vice
- Fillets are common fractions of inch. Should work with imperial tooling.

Unfinished Research

- Design Study
- DOE
- Hand Calc Validation

Hand Calc Of Baseline

· Approximate general shape as cut-off cone without extra material @ wheel hub



X-section equations: $r_2 = mx + 1.53$

$3.63 = m(1.88) + 1.53$

$\Rightarrow m = 1.117$

$r_1 = 1.117x + 1.03$, $r_2 = 1.117x + 1.53$ [in]

· Loading

$W = 372$ lbs

$F_{aero} = 0.76g$

$F_{lat} = 0.73g$

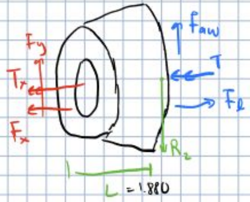
$F_{brake} = 2.2g$

F_ℓ : lateral + = right turn, − = left turn $|F_\ell| = F_{lat}$

F_{aw} : aero + weight $|F_{aw}| = \frac{F_{aero} + W}{2}$ (2 wheeling)

· Internal Cut + Newton's 1st Law

$\Sigma F, M = 0$



$F_x = F_\ell$, $T_x = -T$, $F_y = -F_{aw}$

· Superposition

1) $F_x \Rightarrow$ normal stress

$\sigma_x A(x) = F_x = F_\ell$, $A(x) = \pi(r_2^2(x) - r_1^2(x))$

$$\sigma_x = \frac{F_\ell}{([1.117x+1.53]^2 - [1.117x+1.03]^2)}$$

$\sigma_x(x=0) = \frac{F_\ell}{1.53^2 - 1.03^2}$, $\sigma_x(x=L) = \frac{F_\ell}{(1.117L+1.53)^2 - (1.117L+1.03)^2}$

2) Torsion

$T_x = -T = \int \tau r \, dA$; $\tau = \frac{d\tau}{dr} r$

$$-T = \int_{r_1}^{r_2} \left(\frac{d\tau}{dr} \cdot r\right) r \, 2\pi r \, dr$$

$$-T = \frac{d\tau}{dr} \cdot 2\pi \cdot \int_{r_1}^{r_2} r^3 dr = \frac{d\tau}{dr} \cdot \frac{\pi}{2}(r_2^4 - r_1^4)$$

$$\Rightarrow \frac{d\tau}{dr} = \frac{-2T}{\pi(r_2^4 - r_1^4)} = \frac{-2T}{\pi([1.117x+1.53]^4 - [1.117x+1.03]^4)}$$

$$\cdot\ \tau_{max} = \frac{d\tau}{dr} r_2 = -\frac{2T}{\pi} \cdot \frac{1.117x + 1.53}{[1.117x+1.53]^4 - [1.117x+1.03]^4}$$

$\tau_{max}(x=0) = \frac{-2T}{\pi} \cdot (0.351)$, $\tau_{max}(x=L=0.188) = \frac{-2T}{\pi} \cdot (0.047)$

3) Shear : will use transverse definition

$$\tau_{xy} = \frac{F_y \cdot Q}{I t} = \frac{-F_{aw} \cdot Q}{I \cdot 2(r_2 - r_1)}$$

max @ neutral axis

$Q = \frac{4}{3} r_2^3 - \frac{4}{3} r_1^3$

$I = \frac{1}{4}\pi r_2^4 - \frac{1}{4}\pi r_1^4$

$$\tau_{xy,max}(y=0) = \frac{-F_{aw} \cdot \frac{4}{3}(r_2^3 - r_1^3)}{\frac{1}{4}\pi(r_2^4 - r_1^4) \cdot 2(r_2 - r_1)}$$

$$= -\frac{8}{3\pi} \cdot F_{aw} \cdot \frac{(r_2^3 - r_1^3)}{(r_2^4 - r_1^4)(r_2 - r_1)}$$

$$\tau_{xy,max}(y=0) = -\frac{8}{3\pi} \cdot F_{aw} \cdot \frac{([1.117x+1.53]^3 - [1.117x+1.03]^3)}{([1.117x+1.53]^4 - [1.117x+1.03]^4)(0.5)}$$

Plugging Values:

$\sigma_x(x=0) = \frac{F_\ell}{1.53^2 - 1.03^2} =$

$\sigma_x(x=L) = \frac{F_\ell}{(1.117L+1.53)^2 - (1.117L+1.03)^2} =$

$\tau_{max}(x=0) = \frac{-2T}{\pi} \cdot (0.351) =$

$\tau_{max}(x=L=0.188) = \frac{-2T}{\pi} \cdot (0.047) =$

$\tau_{xy,max}(y=0) = -\frac{8}{3\pi} \cdot F_{aw} \cdot \frac{([1.117x+1.53]^3 - [1.117x+1.03]^3)}{([1.117x+1.53]^4 - [1.117x+1.03]^4)(0.5)} =$

Thank You