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Collapsible Wheelchair Wheel Design

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ABSTRACT

Portability, convenience, and efficiency are becoming more and more prevalent as technology increases. This is also true with wheelchairs; Wheelchairs are being designed to fold and collapse smaller and smaller with every iteration but there is one parameter that remains constant, the wheel. No matter how small the wheelchair frame folds it is always limited by its' wheel's diameter. This project aims to create a collapsible wheel design to accompany a foldable wheelchair in order to make it more portable and storable. Since the diameter of the wheel is the limiting factor in a foldable wheelchair, the relatively small width dimension of the wheel was increased in order to compensate for the reduction of the diameter dimension. This was achieved by creating a wheel composed of six equal parts that interlock to form a solid, functional wheel capable of supporting a human to the weight capacity of other wheelchairs (250 pounds). It is also important that the wheel is easy and quick to assemble and disassemble for users of all ages and capability. It will be tested for strength but also for how quickly it can be assembled and disassembled. To achieve a 1-minute assembly time, quick release hinges were used, an instruction manual was created, and magnet and Velcro attach points were implemented. This collapsible wheel design collapses a standard 24-inch wheelchair wheel to an 11.25 by 10.75 by 6.00-inch assembly. This is a reduction of 83% of its original frontal area when collapsed.

INTRODUCTION

ENGINEERING PROBLEM

The design of this collapsible wheelchair wheel was inspired by folding and collapsing wheelchairs. As technology increases, companies are able to produce compacting wheelchairs smaller and smaller with every version. In most folding wheelchairs, the wheel is the limiting factor for how small and compact a wheelchair can get when folded. No matter how small the wheelchair frame gets, some dimension of its design will have to be the diameter of its wheels. Simply folding a wheel in half still maintains the same diametric length. Therefore, the wheel must be folded three or more times to successfully achieve a smaller length and frontal area. The purpose of this project is to decrease the amount of space a wheel takes up in a folding wheelchair design.

FUNCTION STATEMENT

The function of this device is to fold or collapse into a small, lightweight design that can be stored with or attached to a collapsible wheelchair. When needed, the wheel can easily unfold, lock into place, and function as a structural wheel. The focus is on achieving the smallest amount of frontal area by decreasing the length and height of the collapsed wheel.

REQUIREMENTS

The wheel design will incorporate all of the following parameters:

- The wheel must collapse to less than 50% of its original frontal area.
- The wheel must function as a standard 24-inch wheelchair wheel in everyday situations over various terrain.
- The wheel must contain some form of push rims so wheelchair users can propel the wheel by themselves. Typically, the push rim diameter is 6 inches less than the wheel diameter. Therefore the push rim must have a diameter of 18 inches +/- 2 inches.
- The wheel must be as structurally sound as other wheelchair wheels. Therefore a pair of wheels must be able to support a 250-pound person without fracturing, warping, bending, or buckling. The tire is able to deflect depending on the material used and the weight of the user, but the wheel frame cannot deflect more than 0.050-inch in any location.
- The wheel must weigh less than or equal to 10 pounds.

- The wheel can be folded in 3 minutes and unfolded swiftly within 5 minutes.
- The foldable wheel comes with user instructions for proper use.

SUCCESS CRITERIA

In general, in order to declare this project a success, the wheel will attach to a folding wheelchair and, when folded and collapsed, reduce the amount of space the wheelchair occupies compared to using a standard, non-collapsing wheel. When in use, the collapsible wheel will support a person of maximum weight capacity for 10 hours of use per day, including static and dynamic use.

The folding wheel design is able to replace a standard wheelchair wheel without any structural problems or decrease in weight capacity or performance.

- Can the wheel pair support a 250-pound load when used on a wheelchair frame?
- Under a 250-pound load, it there any measureable strain, bending, or any other failure in the rim, spokes, or hub?
- Is there any failure over rugged terrain such as gravel, dirt, grass, woodchips, etc?
- Can the wheel set withstand curb drops of a standard curb height?

The wheel is easily stored in suitcases, backpacks, lockers, car trunks, airplane overheads, and attached to folding wheelchairs.

- When collapsed, is the frontal area of the wheel less than 50% of its full form?
- Does the wheel contain a push rim that is attachable in some way?
- Does one collapsed wheel weight 5 pounds or less?
- After learning how wheel works, can anyone fold and unfold the wheel in 15 seconds?

SCOPE OF EFFECT

The wheel design applies to compact folding wheelchairs only, predominantly, wheelchairs that are limited in size by the diameter of the wheel when collapsed or folded. See **Figure 1** for examples of ultra-compact wheelchairs. Non-folding wheelchairs have no need for collapsible wheel. Bicycles and collapsible bicycles could benefit from collapsible wheels but are not the focus of this project since foldable push rims are a requirement.

Only the length and height are trying to be optimized in order to produce a shape that is easier to store with a folded wheelchair or in a small location. Therefore, since volume will be conserved, the depth of the collapsed design will increase. In this project, the depth of the collapsed design is not a parameter of concern unless it surpasses the length or height.

FIGURE 1: Examples of ultra-compact wheelchair designs that would benefit from a collapsible wheel.

BENCHMARK

There are a few collapsible wheel designs being sold and some others that are still prototypes. The most common and popular design is the Morph Wheel by Maddak, Inc. [1] It has the following parameters:

- 24-inch wheel diameter by 4-inch depth
- 32 x 12.5 inch (folded)
- 250-pound weight capacity (per set)
- 7.5 pounds wheel weight (per wheel)
- Glass filled nylon material, polypropylene push rim, and solid rubber tire
- $950.00 market price (per set)

FIGURE 2: Morph Wheel by Maddak, Inc.

ENGINEERING MERIT

Design, analysis, and optimization are done in order to reduce the size and maintain functionality. All analysis will relate to the requirements of the project. Equilibrium equations ($\Sigma F_x = 0$, $\Sigma F_y = 0$ and $\Sigma M = 0$) will be used to determine the resultant forces from the material weight and required 250-pound weight capacity for the wheel pair. Stress and strain analysis due to bending (Mc/I) and tension/compression (P/A) will be used to determine thickness, shape, location, and design of the spokes, hub, rims, and connecting parts, as well as other methods of analysis such as critical buckling loads, fatigue stress, stress concentrations, and safety factors. Material and treatment will be selected depending on stress and strain results and material properties in order to optimize for increased strength, reduced weight, and minimal frontal area.

DESIGN & ANALYSIS

APPROACH

In order to decrease the length of a 24-inch wheel, the wheel must be folded into three or more segments. If only folded once the wheel would still be 24 inches in length even though the height was cut in half. Also, the design of the benchmark, the Morph Wheel by Maddak, adds length to improve height. This is not the focus of this design. This project focuses on adding length to the (already small) depth dimension. The focus is that it is easier to store and carry a 10x7x7-inch cube of material than a 24x1-inch wheel whether in a backpack, on an airplane, or attached to a folded wheelchair.

DESCRIPTION OF DESIGN

To achieve a collapsing wheel that outperforms the Morph Wheel benchmark, a different design needs to be implemented. The first thing that comes to mind is folding a wheel in half and then folding it in half again, making it a quarter of its original frontal area. There are some unnecessary issues in this design, though, such as folding the axle bearing. To avoid this, the idea of a multi-piece wheel of equal sizes that could fan into position was considered. Instead of messing with the axle hub, the multiple wheel parts would rotate around the axis and lock into a full wheel at 360 degrees. There is nothing being commercially produced or sold that collapses in a fan-like motion for wheelchairs, though there are prototypes and a few designs for bicycles on the internet.

The initial concepts were a three-piece wheel, a four-piece wheel, and a six-piece wheel. See **Figure 3** for sketches of the initial designs. The three-piece wheel only slightly reduced the width by 2% since the angle between spoke beams is 120 degrees. The six-piece wheel had the smallest width and height but for a tire thickness of 1-inch times 6 folds would yield a depth of 6 inches. Plus, in this particular design, the axle hub is not part of the compact design, leaving more area used up. The four-part wheel was the best design to move forward with. It cut the width and height in half and only increased the depth by a factor of 4. At this point, a five-piece design was also necessary to look into.

Next, the concept of how much "space" the collapsed wheel design would take up was determined. The idea is to reduce the area of a largest side of the wheel. This is because the 24-inch diameter of the wheel is the limiting dimension for many foldable wheelchairs and what makes storing a wheel when traveling or when put in storage the most cumbersome. The 4-piece, 5-piece, and 6-piece wheel designs were compared to determine what design to progress with.

According to some simple geometry seen in the **Appendix A pg. 1**, the 4-piece wheel has the largest frontal area of 115.5 in.^{2} but the smallest depth and volume of 4 in. and 461.8 in.^{3}, respectively. The 6-piece design had the smallest frontal area of 78.0 in.^{2} but the largest depth and volume of 6 in. and 468.1 in.^{3}, respectively. So what can be determined? Looking at the requirements, each design is less than 50% of the original frontal area. A push rim would be the easiest to install on the 4-piece wheel because it allows for more mounting surface area. The 4-piece design also has less locking parts and would be the most structural design since there are fewer locations for failure to occur. Lastly, the requirement of quick and easy assembly and disassembly also benefits from the 4-piece wheel design since there are fewer points to lock and unlock.

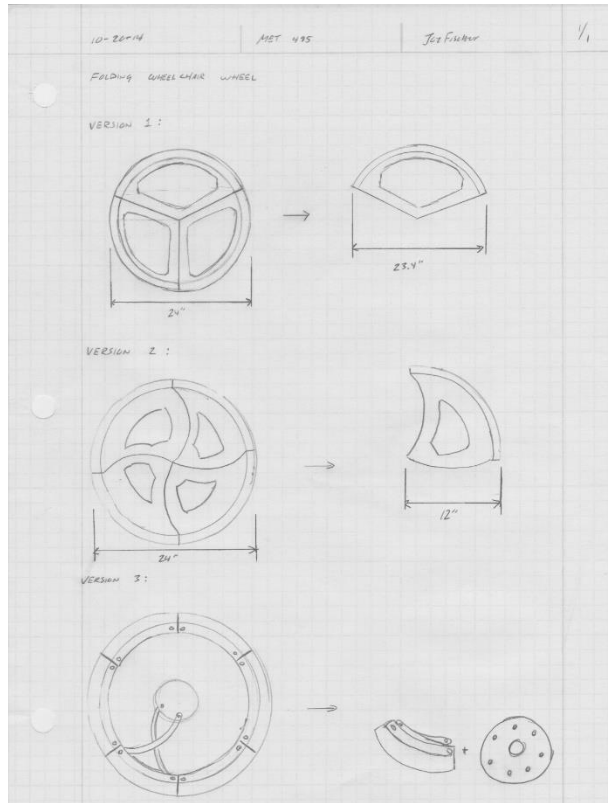


FIGURE 3: Initial concepts for the collapsible wheel.

TABLE 1: Comparing Number of Wheel Pieces			
WHEEL DESIGN	**4-Piece Wheel**	**5-Piece Wheel**	**6-Piece Wheel**
Frontal Area	115.4 in.^{2}	93.0 in.^{2}	78.0 in.^{2}
Area Reduction	74.4%	79.4%	82.8%
Depth	4 in.	5 in.	6 in.
Volume	461.8 in.^{3}	465.0 in.^{3}	468.1 in.^{3}
Locking Areas Req.	4	5	6
Assemble Speed	Fastest	Moderate	Slowest

At this point, more emphasis and analysis was put into the 4-piece design. That being said, the 5-piece and 6-piece designs were not dismissed. More analysis will be put into the 5- and 6-piece designs in the following analysis section. A new, further-developed version of the 4-piece wheel was conceived with more in depth features, movement, and geometry in **Figure 4**. The CAD design was given initial shapes and dimensions based on other wheel designs as a starting point for analysis. These design choices would be analyzed in the following analysis section and ultimately changed to optimize the conditions set by the requirements such as frontal area, weight, and maximum load capacity.

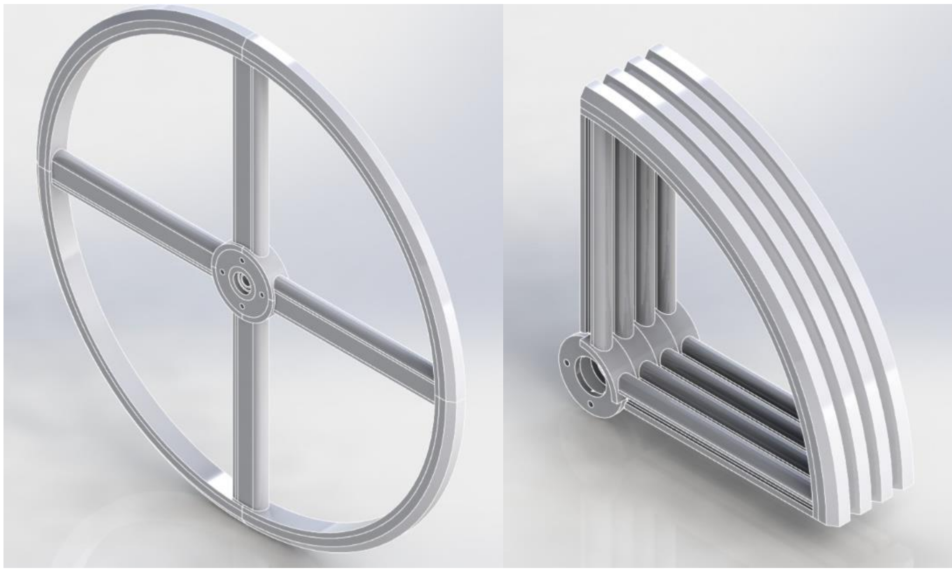


FIGURE 4: 3D model of Version 1.0 4-piece 4-spoke collapsible wheel design in an open (left) and closed (right) position.

Next, the implementation of an intermediate spoke was added based in order to increase the load capacity and allow for a push rim to be attached. The spoke is positioned at the interior of the rim and hub to allow the push rim to fold inward when the wheel is in its collapsed state. This spoke was also given an arbitrary shape and dimension until more structural analysis was done. There were initially two designs for the push rim. Since the wheel parts are flush with one another in its collapsed state, the push rim could not be allowed to remain jutting out from the wheel body as more wheelchair push rims do. The push rims needed to be able to jut out when in use and then be maintained inside the depth of the wheel when collapsed. See **Figure 5a and 5b.**

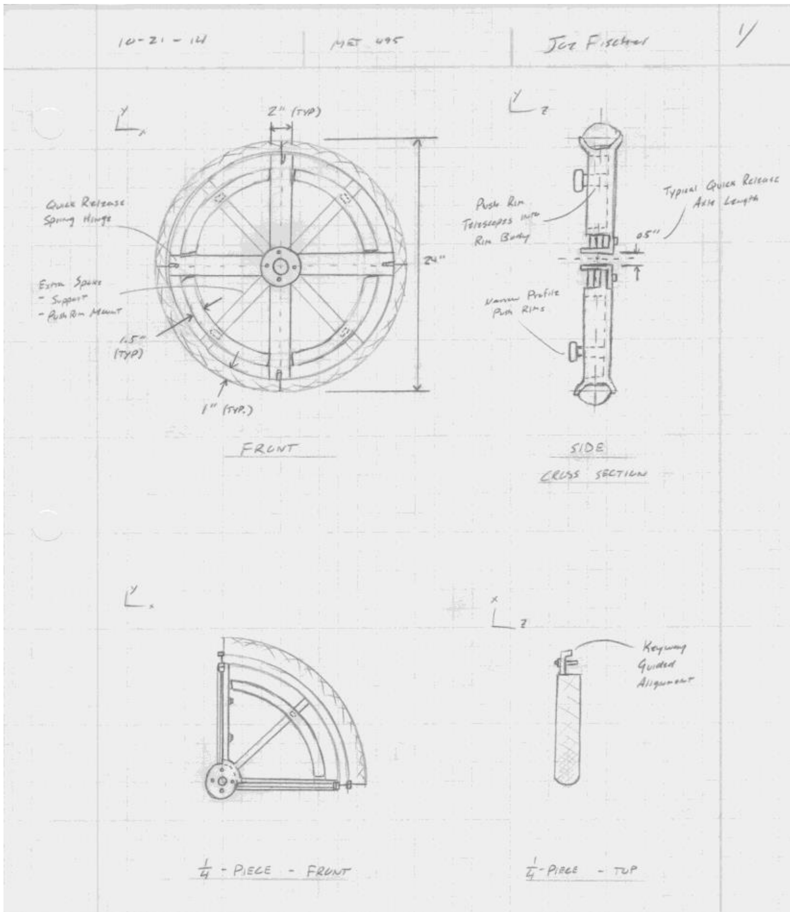


FIGURE 5a: Version 1.0 of the 4-piece collapsible wheel.

FIGURE 5b: Version 1.1 CAD model of the 4-piece 8-spoke collapsible wheel in an open (left) and closed (right) position.

A new push rim design was created to allow for more stability. This design was inspired my peg-style wheelchair push rims and foldable scooter handlebars. See **Figure 6**. This new handlebar design for the push rim required more locations for mounting; therefore a curved surface was placed between the main spoke beam and the intermediate spoke beam. With this setup, 4 to 12 handles could be easily mounted to the wheel while also folding inward when collapsing the wheel. Also, the method in which the four wheel quadrants assemble to the hub was redesigned to allow for welding clearance. This redesign also allowed for easier manufacturing.

When evaluating the design of the 6-piece wheel, more push rim designs were considered. A compromise of both a circular push rim and a peg-style push rim was ultimately chosen. A mid-spoke aluminum plate was designed to allow both a removable circular push rim and removable rotating push bars to be mounted to the wheel depending on the preference of the user. See **Figure 9** for push rim designs.

FIGURE 6: Peg-style push rim (left) courtesy of Quickie-Wheelchairs and Razor brand detectable handlebars (right).

A 6-piece design was created to compare with the 4-piece design. The results can be seen in the following Analysis section. This design incorporates more construction time, more assembly time for the user, and a larger depth dimension. But this design does decrease the frontal area of the collapsed wheel, which is the primary requirement. The 6-piece wheel follows a similar design to the 4-piece wheel but contains no mid-spoke. Also, at this time more possibilities for materials were considered. First, aluminum was considered for its strength and relatively low weight for a metal alloy. Second, glass filled nylon was considered since it is commonly used in wheelchair wheels. It is a good material because of its high strength for a polymer and low-weight compared to aluminum. These two types of material have an overlap in term of density to strength ratio as seen in **Figure 7** [5]. The major drawback for nylon is its cost. Next, other polymers that are more cost effective were considered such as acetal, acrylic, PEEK, ABS, and others. Also, other aluminum alloys were considered such as 2024, 6063, 1100, etc. Since aluminum 6061-T6 was more strength than needed, other aluminum alloys with lower densities were considered. A comparison of needed mechanical properties, density, and cost of considered materials can be seen in **Figure 8** and the 6-piece design can be seen in **Figure 9**. These material values were obtained from www.matweb.com [2].

After comparing prices, 6061-T6 is the most common, most available, and best strength for the price. At about 1/6 the cost of glass filled nylon, aluminum 6061-T6 is the most reasonable choice material. The only drawback is the aluminum weight. Though aluminum is considered lightweight compared to other metals, it has about twice the density of nylon at 0.0975 lb/in^3. This may affect the maximum weight requirement of the wheel. But with its greater strength, less material will be needed to achieve the same rigidity as the nylon. Aluminum also has better machinability than nylon and is able to hold a tolerance better since it is not a polymer and does not absorb moisture like nylon. This is very important since the tolerances, especially in the spokes, need to be strictly followed.

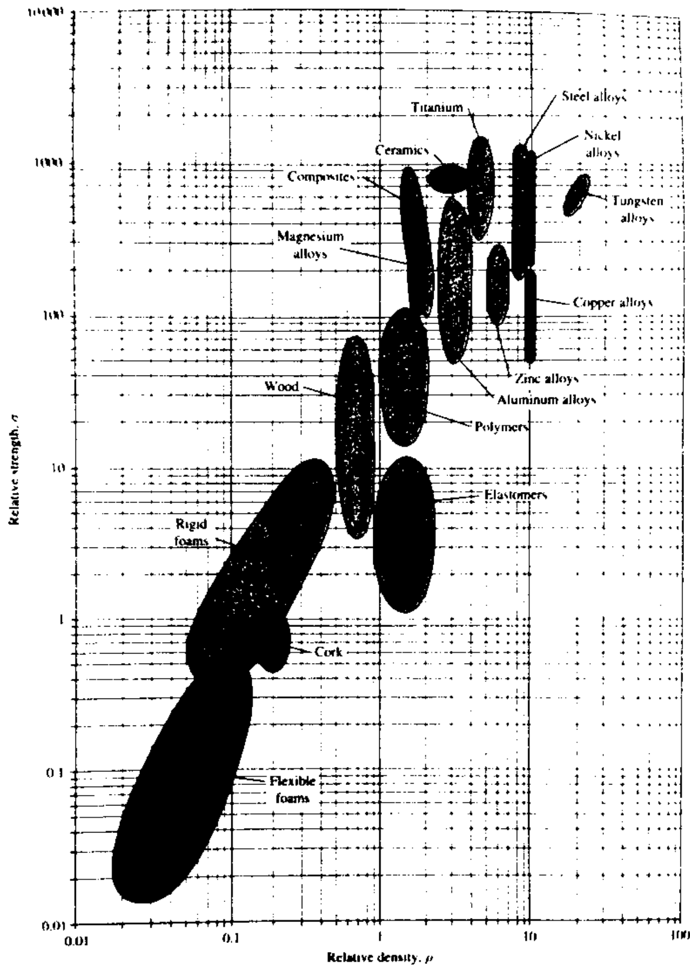


FIGURE 7: Density to strength comparison of different materials.
Mott, Robert. "Machine Elements in Mechanical Design", pg. 77

POLYMER COMPARISON

Source: www.onlinemetals.com

Size: 1 unit = 12"x12"x1"

NYLON 101 PA66	
Tensile	12000
Shear	10000
Density	0.0415
Cost	87.33

NYLON GS PA66	
Tensile	12500
Shear	10500
Density	0.0415
Cost	112.73

ACETAL	
Tensile	9500
Shear	8000
Density	0.0509
Cost	114.79

ACRYLIC (CAST)	
Tensile	10000
Shear	17000
Density	0.0433
Cost	44.3

POLYCARBONATE (MACHINE GRADE)	
Tensile	9000
Shear	10000
Density	
Cost	172.63

HDPE	
Tensile	4600
Shear	3000
Density	0.0343
Cost	32.13

PET	
Tensile	11500
Shear	13000
Density	0.0499
Cost	200.63

ALUMINUM COMPARISON

source: www.matweb.com
www.onlinemetals.com

size: .75"x1"x10"

ALUMINUM 6061-T6	
Tensile	40000
Shear	30000
density	0.0975
cost	4.28

ALUMINUM 6061-T4	
Tensile	21000
Shear	24000
density	0.0975
cost	4.00 – 5.00

ALUMINUM 6063-T6	
Tensile	21000
Shear	17000
density	0.0975
cost	8.45

ALUMINUM 2024-T3	
Tensile	47000
Shear	41000
density	0.1
cost	11.03

ALUMINUM 7075-T6	
Tensile	63000
Shear	48000
density	.1013
cost	18.05

FIGURE 8: Comparison of optimal materials based on desired physical properties, weight, and cost

The design of the spoke was initially to cut a 1-inch wide column in half. A new design which allows the two spoke halves to interlock was conceived to ensure the two halves would act as one beam or column under load, thus increasing the cross sectional area of each spoke and increasing the allowable stress each spoke can withstand. The interlocking spoke halves act as a keyway. They have equal and opposite cross sectional geometry to allow for easy manufacturing. It is important to allow enough depth of cut for the keyway to ensure the two halves lock securely but also that the wall thickness is thick enough to not shear under load. The dimensional tolerances of the keyway will be another important factor since the keyway must fit flush with its mate. If too large the key will not fit and if too small the key will rattle inside the keyway. There are three modes of locking the individual wheel sections together. First, the bolts connecting the wheel sections to the hub prevent movement in all directions towards the bottom of the spoke. Next, the interlocking spoke keyway prevents a vertical spoke from movement in the x-direction and the negative z-direction along the spoke length. Last, the spring latch prevents movement in the positive z-direction towards the top of the spoke, ensuring the spoke halves stay locking in the keyway and also keeping the rim and tire sections aligned.

Lastly, the wheel sections must stay together as one cohesive unit when the wheel is in its collapsed state. Many idea were considered for this feature. The most practical and least obtrusive is to use inset magnets on the rim and hub to lock the wheel sections into place. A specific size of magnet will have to be chosen in order to be strong enough to keep the wheel together, and weak enough to allow the user to detach it when needed. Additionally, an appropriate method of fixing the magnet to the wheel will depend on the size and location of the magnet.

FIGURE 9: 6-piece wheel design 2.0. Attachable handle push rim configuration (Top), attachable circular push rim configuration (Middle), and collapsed configuration (Bottom).

DESCRIPTION OF ANALYSES

Most of the engineering merit will come from the requirements of functionality and structural integrity. Choosing the correct materials, the shape, the thickness, the length, and how they interact will depend on static equations involving force, torque, inertia, stress, strain, mass, etc.
Equilibrium static forces would first be calculated for the spokes using $\mathbf{\Sigma F_x=0, \Sigma F_y=0, \Sigma M=0.}$ The number of spokes being used can control the amount of force. The more spokes in each wheel segment, the more distribution of the maximum capacity load applied at the axle. Though one of the requirements is to keep weight of the wheel to a minimum so a

balance of number of spokes, shape, and material must find a compromise.

Next, in order to determine shape and material, stress due to tension, compression, bending, and shear can be calculated using $\boldsymbol{\sigma} = \mathbf{P/A}$ and $\boldsymbol{\sigma} = \mathbf{Mc/I}$. Using the radial and tangential forces calculated and a standard cross-sectional area for common wheelchair wheels, the max stress can be calculated. At this point, a material can be selected or, depending on the max stress, a new number of spokes or cross sectional area can be used to calculate a new max stress that will result in a more lightweight material capable of resisting the maximum load on the wheel. Next, using Young's Modulus, strain can be calculated using $\mathbf{E} = \boldsymbol{\sigma/\varepsilon}$ depending on the material determined prior. Once the strain is known, deflection can be calculated using $\boldsymbol{\varepsilon} = \mathbf{L - L_0 / L_0}$ and $\mathbf{y_{max} = FL^3/3EI}$ since a maximum deflection is one of the requirements. Buckling is another important parameter that needs to be analysis. The critical load can be calculated using $\mathbf{P_{cr}} = \boldsymbol{\pi}^2\mathbf{EI/(KL)^2}$. This equation will affect my material choice, the cross sectional area, and the length of the spokes.

PERFORMANCE PREDICTIONS

A few parameters can be determined right away by looking at the benchmarks and looking at other wheelchair wheels in general. First, based on other wheelchair wheels, the material will be a light metal alloy or a hard plastic. It can also be determined that the collapsible design will require 4 to 10 spokes in order to meet the requirements regarding structure and minimal frontal area. Another prediction is that the spokes must be larger than wire spokes in order to account for some form of attachment and separation to occur.

The main requirement is that the frontal area is less than 50% of the uncollapsed wheel design. With the 4-piece and 6-piece designs being considered, it can be predicted that the frontal area will be between 20% and 30% of the uncollapsed form. This is because the 4-piece design reduces the area by a quarter of its original area, plus the area of the axle hub would yield approximately 30%. With the 6-piece design, the collapsed area would be one sixth plus the axle hub for approximately 20%. According to the CAD model of the final version of the 6-piece wheel, the collapsed area will be 71.9 square inches, a reduction of 83.4% from its uncollapsed form. The predicted dimensions of the uncollapsed wheel is a standard 24-in. diameter by 1 in. depth. When collapsed the dimensions are predicted to be 11.25 x 10.75 x 6 in. The weight is predicted to be 10.9 lb. based on the CAD design mass properties feature of the final version of the collapsible wheel. At this time, this is 0.9 lb. over the target weight goal.

After looking at many styles of wheelchair wheels, the height and width of the spokes for a 4- to 8-spoke design will be between .5"x.25" and 2"x1.5" depending mainly on the material. Added more spokes could reduce the thickness of the spokes but adding more spokes could also add more weight. Since this design requires the wheel to separate, the spoke columns need to be thick enough to attach and detach in some way. The most optimal choice would be a minimal amount of spoke for lightweight, ease of assembly, and required width to allow for attachment points. The predicted design is a 6-spoke configuration with 1" x .75" rectangular cross sections for easy interlocking.

The cost of one wheel is predicted to be $162. Comparing this to the competitor benchmark of $950 per set, this project's wheel will be 62% less expensive to produce excluding retail mark-up costs.

If a polymer is used, it may be expensive and hard to find a plastic with the strength and machinability needed for this project. Plastic may prove to be the best choice for auxiliary parts like the push rim since many wheelchair models already used a polymer material for their push rim and/or push bars. These parts will most likely be purchased and retrofitted onto the project.

If aluminum is used for the frame, there will be less of an issue with deflection and stress than that of a polymer such as nylon but at the cost of more weight. A6061-T6 will be used and have a yield strength of 40 ksi and an adjusted yield of 20 ksi with the safety factor of 2.0. With the spoke geometry and a safety factor of 2.0, the spokes will fail due to bending at 250 lb per wheel, or 500lb together.

ANALYSIS

After setting up the initial design as a 4-piece, 4-spoke collapsible wheel that splits mid spoke, analysis was conducted to see how much force would result in each spoke given the 250-pound weight capacity. At this point, material weight was neglected as a force since material would be decided depending on the results of this analysis and the following. The analysis was done in a 0 degree position where the bottom spoke was perpendicular to the ground and also at a 45 degree position to help determine a maximum force due to the load. At 250 pounds distributed over two wheels, the force in each spoke was 15.6 pounds in the 0 degree position and 22.1 pounds in the 45 degree position. Analysis can be seen in **Appendix A pg. 2**.

This analysis was conducted again with an intermediate spoke added totaling 8 spokes in a half spoke – full spoke – half spoke design as shown in **Figure 5a** and **Figure 5b.** The addition of an extra spoke decreased the load on each of the spoke-halves to 10.4 pounds: a reduction of 33%. These extra intermediate spokes also serve a second purpose as positions to mount the collapsible push rim. This is essential since the half-spokes do not provide much area to allow for attaching push rim mounts. This analysis can be seen in **Appendix A pg. 3.**

Average tension and compression stresses were then calculated in the spokes using the forces calculated in **Appendix A pg. 3**. The resulting stress in the linking half-spokes was 27.8 psi and 78.6 psi for the intermediate push rim-mounting spokes. Since there is a significant disparity in stress between the two types of spokes, increasing the cross sectional area (mainly the width) of the intermediate spokes to reduce the 78.6-psi stress may be a good idea. See **Appendix A pg. 4.**

A safety factor will be set initially at 2.0 since the number of cycles in which stress is applied in the spokes, rim, hub, etc. is fairly large for endurance stress. When the wheel is not turning but someone is still sitting in the wheelchair, the wheel is still subject to static loading. A 2.0 safety factor ensures the wheel will support twice the amount of weight per wheel. This is good since many wheelchair users may be over 250 pounds. Also, there is a larger impact force from “plopping” into the wheelchair seat or dropping off a curb or ledge.

Next, each spoke beam of the 4-piece design was analyzed as if the maximum load was acting on that beam alone to ensure no failure. With a maximum load of 250 pounds split between two wheels, each wheel must support 125 pounds. In **Appendix A pg. 6 - 7**, tensile, compressive, bending, and buckling forces were calculated using the shape and orientation of each beam in relation to the load location. The appropriate stresses were then calculated using “place holder” values for the cross sectional area of the beams. An Excel spreadsheet was created in **Appendix A pg. 5** so try different base and height values for each beam and compare the resulting stresses with the yield strength of materials being considered. At this point, aluminum 6061-T6, nylon 6/6 10%, and nylon 6/6 20% were the materials being considered. The spreadsheet accounted for beams in tension, compression, bending, buckling, and combined loads. Specifying a safety factor of 2.0, the spreadsheet takes into account the length of the spoke beams, the load being applied, and the material properties (received from matweb.com). With those values fixed, a base and height value for the cross sectional area can be selected for each beam to determine if that beam is under the yield strength adjusted with the safety factor. For the 4-piece design, nylon 6/6 10% fails for some spokes but the 20% nylon and aluminum do not fail. Since the density of the nylon is 0.0462 lb./in^3 and aluminum is 0.0976 lb./in^3, the nylon 20% is selected since a maximum weight is a requirement. The spoke dimensions were 1”x.75” for the main spoke and 1.5”x.25” for the intermediate spoke in order to stay under the yield stress of nylon 20%. Dimensions could have been increased to use nylon 10% but since there isn't a significant difference in cost and only a 0.003 lb./in^3 difference in density, nylon 6/6 20% glass-filled is optimal for weight, strength, and size.

Next, the deflection of each beam would be analyzed to satisfy the maximum deflection requirement. See **Appendix A pg. 9-10**. At this point, 20% glass filled nylon was being considered. To ensure no failure, the deflection for each spoke was analyzed independently with the 125-pound load at the axle. The deflection of the horizontal spokes was 0.040". At the 45-degree intermediate spoke 0.057" was calculated. And for the vertical spoke, a deflection of 0.002" was calculated. These deflection values are satisfactory for the requirement and the actual deflection will actually be less since the calculation did not take into consideration fillets and weld spots.

Next, a new Excel spreadsheet similar to **Appendix A pg. 5** was set up for the 6-piece wheel design to compare the resulting stresses to the 4-piece wheel design. Where the 4-piece had 4 main spokes and 4 intermediate spokes, the 6-piece design has 6 main spokes and an offset curved base between each spoke to support a push rim. With this new design, dimensions of 1" x 3/4" could be used for the cross section of the 10" spoke beam. This is the same as the 4-piece design but with fewer spokes, therefore less material, therefore less weight. This allowed for a base length of 3/4" for the right and left side of the mating spokes. Therefore there is an overlay of 1/2" in which the keyway will be cut. A keyway with a 1/4" fits perfect perfectly center with a 3/4" base length. A 1/4" keyway also allows for easy machining since it is a standardized machining tool size. See **Appendix A pg. 11-12**.

Finite element analysis was also done in SolidWorks with the new spoke dimensions. See **Appendix A pg. 15.** Though not entirely accurate, these analyses help get an idea of the amount of stress and deflection for the dimensions and material chosen. The analysis was conducted two ways: first, assuming an individual beam took the full load from the axle and, second, as a whole system. For a single spoke in compression from the 125 lb. load, the spoke would not yield with a safety factor of 2 and the maximum deflection would be 0.0058mm, which is equivalent to $2.28\text{x}10^{-4}$ in. This can be compared to the deflection calculations in **Appendix A pg. 10** of $1.6\text{x}10^{-4}$in. This may be due to a different method in calculating deflection or slightly different modulus of elasticity values. Note that the maximum normal stress in the column is $2.196\text{x}10^6$ N/m^2 and does not exceed the yield strength. The maximum stress occurs around the bottom and top corners of the column but in actuality these columns will be welded at those points, making those points the strongest locations on the column.

A single horizontal spoke would be subject to bending stress from the 125 lb. load at the axle. Assuming only one beam is subject to the load, the beam would not pass the yield point. See **Appendix A pg. 16**. Note there is an error with the von Mises color-coded scale. This is because a small extruded surface had to be made so a point load could be applied. The maximum stresses on the scale are actually from the edges of the extruded base. Noting the color of the beam, the actual max stress is somewhere in the blue region. Compared to my hand calculations in **Appendix A pg. 12** and the Excel spreadsheet in **Appendix A pg. 11**, the maximum bending stress is 10000 psi, which is $69\text{x}10^6$ N/m^2. That puts the maximum bending stress between the first and second hash mark on the color scale, which is well below the yield marker. The maximum deformation is 2.987mm, which is equivalent to 0.118 in. This is the same deflection value calculated in **Appendix A pg. 14**. A deflection of 0.118 in. is greater than the 0.050 in. maximum deflection in the requirements. However, in the second part of the analysis in **Appendix A pg. 14,** in actuality the applied force will be between two horizontal beams. The deflection for a mid-beam force that is fixed on both ends is 0.007 in. This is far below the requirement deflection and this analysis ignores the other non-horizontal spokes supporting the load. Since the deflection in the vertical spoke is only $2.28\text{x}10^{-4}$ in., the deflection of the horizontal spokes would be dependent on the deflection of the vertical spokes.

Endurance strength of the spokes was also analyzed since the wheel is subject to dynamic loading. As the wheel turns, there are fluctuating stresses in the spokes. There is a minimum normal stress when the spoke is in a vertical position and a maximum bending stress when the spoke is in a horizontal position. The Goodman Method for Fluctuating Stresses of a Ductile Material was used to calculate the adjusted endurance strength of 11.5 ksi, which is less than 20 ksi, the fatigue limit of A6061-T6. The stress amplitude is 6,583 psi for this situation. Using Figure 5-7 in "Machine Elements of Mechanical Design" by Robert L. Mott, it can be observed that the number of cycles this wheel can endure before failing is greater than 10^7. It can be approximated that the number of cycles is 10^9 by looking at the chart. If it is assumed the wheel rotates at 1 cycle every 2 seconds (which is generously fast) and the wheel is in constant motion every second of every day, the wheel will last 63 years until it fails due to fatigue. This is impressive but does not take into account impact loads and others modes of failure that could happen before the wheel fails to fatigue. See **Appendix A pg. 20**.

Next the deflection of the tire rim was analyzed. The rim used was purchased and modified since a rim could not be machined due to the limitations of this project as discussed in the Design Section. Because of its irregular cross sectional area and curvature, the rim had to be analyzed using the FEA in SolidWorks. The rim was fixed at the location of the spokes and the resultant force of 125 lb. was placed at the midpoint for maximum deflection. The maximum stress was loaded towards the center of the rim and was 38,900,000 N/m^2, or 5,600 psi. The yield stress adjusted with a safety factor of 2.0 is 20,000 psi, therefore the rim is safe under maximum load. The maximum deflection was 0.076mm, or 0.003in., which is also below the requirement. Note this not taking into consideration the rubber tire since SolidWorks cannot analysis a two-body part. Since the tire is rubber, it will absorb some of the force and deflection, thus reducing the actual stress and deflection on the rim and spokes itself. See **Appendix A pg. 17**.

Next, analysis was done on the hub spoke base. This part was responsible for bolting the wheel sections onto the axle hub. Two spoke halves will be welded to the base and will then be able to bolt onto hub plate. As one of the three methods of locking the wheel pairs together, it is important this part does not fail. First the part was analyzed in SolidWorks as if it was in compression (below the axle as the wheel turns) and then again in tension (above the axle). See **Appendix A pg. 19.** In the compression test, the machined lip, as mentioned in the Design Section, helped relieve some of the stresses and deflection. The largest amount of stress was, of course, at the corner of the lip but was only 516 psi with a deflection of 1.97×10^{-5}in. In tension, the maximum stress occurred at the bolt hole but was only 1,073 psi with a maximum deflection of 1.42×10^{-4}in. at the outer lip.

To further examine the stress at the hole, hand calculations for stress concentration was done for the spoke base section. See **Appendix A pg. 22**. In a static scenario, the calculated normal stress was 933.4 psi. This is comparable to the 1,073 psi stress estimated in the SolidWorks FEA. In both cases the stress I far below the adjusted yield strength for aluminum and the deflection is below the requirement. The Goodman Method for Fluctuating stresses was also used to determine endurance stress of the part since the wheel will be in motion for a good percentage of its use. Adjusted endurance strength of 9,201.6 psi was calculated for this part. This led to a recommended safety factor of 3.45, which is greater than the 2.0 being used. The yield strength adjusted with a 3.45 safety factor is 11.6 ksi, which ensures the spoke base is still safe. Also, using the stress amplitude (466.7 psi) calculated for the Goodman Method, the number of cycles before failure could be observed from Figure 5-7 in "Machine Elements of Mechanical Design" by Robert L. Mott [5]. For aluminum 6061-T6 at 466.7 psi stress amplitude, the number of cycles was off the chart (greater than 10^7). This is good since the wheel will be subject to many cycles because of its constant use.

It was also important to analyze the bolt holding the spoke base to the hub plate. See **Appendix A pg. 21**. Assuming the bolt takes the full 125-lb load and the other two methods of locking the wheel sections in place are not affecting the force on the bolt, the 1/4" bolt is subject to 1273.24 psi of shear stress. The strength of a Grade 2 steel 1/4-20 bolt, as provided from the distributor, is 7,500 psi of shear stress. It is also mentioned that the bolt can withstand 200lb. at the thread and 370lb. at the bolt. With 6 bolts being used, this checks out as a safe size bolt to use in both scenarios.

SAFETY FACTOR & METHODS OF FAILURE

The spoke geometry was designed in such a way so that a safety factor of 2.0 would allow the wheel to fail at double the required load capacity. The standard wheelchair has a maximum weight capacity of 250 lb. but two wheels will fail in bending at 500 lb. See **Appendix A pg. 11**. The wheel will fail due to shear and bending stresses in the spokes from loads greater than 500 lb. Other locations analyzed in Appendix A demonstrate the spokes will be the first mode of failure, specifically the spokes in a horizontal orientation as analyzed in **Appendix A pg. 12**. The stress and deflection of the tire rim was also a concern for failure since the wall thickness and design was left to the manufacturer. The aluminum tire rim is also at its weakest state when the wheel is in the same orientation as **Appendix A pg. 12.** As revealed in the Analysis Section and **Appendix A pg. 17**, the rim will experience 5,600 psi of stress from the maximum load and will not fail with the same safety factor of 2.0.

METHODS & CONSTRUCTION

DESCRIPTION OF CONSTRUCTION

Processes for construction of wheel include:

- Welding. Heli-arc for aluminum. Plastic welding if needed.
- Milling, lathe, CNC machining custom parts.
- Grinding and finishing.
- Tapping threads.
- Use of purchased parts and modified parts from production model wheelchair and bicycle wheels.

See **Appendix B** for the full list of technical drawings and **Appendix C** for a correlated drawing tree of the steps, materials, and processes needed to complete this project.

First, the axle hub will be constructed since much of the alignment and dimensions of the attached spoke come from the hub, especially the hole locations. The hub will use purchased 1/2" wheel bearings pressed into an aluminum cylinder. The base plate will be cut turned on the lathe to the correct diameter and a hole will be drilled in order to fit and weld the bearing cylinder in.

Second, the bases for the spokes need to be made. The six bases start as a single cylinder of aluminum. The cylinder is turned to size and the center hole is drilled. The counter bore on the back is also turned on the lathe using an inside facing tool bit. The cylinder is then cut into six equal quadrants using the band saw. The holes for the hex bolts can then be drilled through both the spoke base and hub plate at the same time to ensure the holes line up correctly.

Next, the spokes will be machined to the correct base and height values (3/4” x 3/4") out of the 10” aluminum stock. The keyway will then be machined on the vertical milling machine. Tolerances will be crucial at this point or else the two halves of the spoke will not mesh properly. Once the two halves mesh properly, the end of the spoke that is to be welded to the base must be rounded to fit the diameter of the base. The spokes are then welded to the bases at the correct distance from the bottom face. This will require a custom jig to assure the spokes are 60 degrees apart and that the spokes are the correct depth into the wheel.

Both the solid rubber tire and the aluminum tire rim are purchased parts but will be modified to fit this project. Both the rim and tire will need to be cut into 6 equal pieces. This may require a jig or some careful measuring and layout. The tire and rim sections will be joined with an epoxy or contact specifically for aluminum on rubber contact. The spring latches are also purchased and modified. The width will need to be cut to size and hole locations need to be drill for mounting to the spokes.

The finished product will also include a User Manual with instructions on how to assemble and disassemble the wheel correctly and efficiently. This is important for meeting the required user self-assembly time and ease of use in the Requirements Section, as well as Test 3: Assembly Efficiency in the Testing Section. See **Appendix J** for Collapsible Wheel User Manual.

PARTS LIST

Parts for this project will include machined parts, purchased parts, parts taken from existing wheelchair and bicycle models, and modified parts. A complete parts list can be seen in **Appendix C**. An overview of the parts include:

- Standard 1/2” wheelchair wheel bearings
- 24” x 1” solid rubber tire
- 24” x 1” aluminum tire rim
- Aluminum cylindrical hub
- Hub Plate
- Steel 1/4” – 20 UNC x 1” hex flange bolts
- Spring loaded pin latches
- Aluminum spokes
- Aluminum spoke bases

Each part has a respective technical drawing associated with its Part Number in **Appendix B**. Parts in the parts list are arranged into three subassemblies (A, B, C) depending on their Part Number. The prefix BC indicates the part is used in both subassembly B and C.

MANUFACTURING ISSUES

Time way a large factor in terms of how much was accomplished on this project. 90% of the parts were manufactured out of raw material for this wheel, and many of the purchased parts were modified. There were also cutting errors on some of the manual operations for the spokes and hub in which new material had to be repurchased and cut again.

Another issue that was addressed was the tire and rim assembly. These were purchased for a specific reason since the tire was solid and could be segmented. Once segmented, the rubber tire shrank and did not fit the new collapsible wheel assembly. A new tire was obtained and cut again, this time compensating for the percent of shrinkage that occurred the first time. The matching tire rim was specifically chosen because it was aluminum and needed to be welded to the spokes, which are of the same material. But what was not mentioned was that the rim was anodized, so the rim had to be sanded before welding.

Lastly, there were issues with tolerances during the welding process. The tolerances on the spoke slots were deliberately small in order to support stability and the sections locking into place. But in order to keep the tight tolerances like the ±0.005” wide slot, for example, the welding had to be set up perfectly. During the welding process the extreme heat causes the material to warp and bend. Jigs were set up and the work piece was clasped to the best of its ability, but ultimately the spokes still warped 1 to 3 degrees. This caused some of the slots to not line up. In order to fix this, the slots were grinded and chamfered to allow the sections to fit together.

TESTING METHOD

INTRODUCTION

This project will be tested in Quarter 3 starting March 2015. The first method of testing will include strain gauging specific areas of interest including the spokes halves, the tire rim, and the hub under the maximum capacity load. These measured values will be compared to the analysis calculations and finite element analysis. It is important these critical locations do not fail or deflect past the design requirement. Since this project is intended for the elderly, handicapped, and people in general, it is crucial the wheel does not fail.

APPROACH

Since the purpose of this project is to produce a wheel that is as compact as possible, it is important to test the size and weight of the wheel after constructed, both collapsed and open. The requirement states that the wheel must collapse to less than 50% of its original area in order to compete with its competition. The requirements also state that the wheel must weigh less than 10 pounds to be considered a success. This will be done by traditional measuring methods and compared to the predicted dimensions and weight along with the benchmark and other portable wheelchair wheels on the market.

The collapsible wheel will be attached to the wheelchair axle and loaded to 250 lb. Strain gauge measurements will be taken at critical locations. This will be repeated several times. The strain will also be measured in linear motion as well as over rigid terrain and over ledges. It is also important to test other shock loads, as elderly and injured wheelchair users are often “popped” into their wheelchairs, causing extra stresses in the wheels. [8] This will be repeated with increased loads up to 500 lb. to verify the calculations with a safety factor of 2.0.

The Tinius Olsen in the Hogue Technology Building will be used to test individual spoke columns to determine maximum tensile stress and deflection. For this test, additional spokes will be manufactured. The results will be compared to the analysis and FEA results.

According to the requirements, the wheel must easily fold and unfold within 60 seconds and contain a set of instructions for proper use. Many time trials of folding and unfolding the wheel will be conducted to gauge whether or not this design meets the benchmark for ease of use and efficiency. This will be performed by different people of different ages multiple times after carefully reading the provided instructions.

PROCEDURE

TEST 1: Assembly Efficiency Test
Appendix H - pg. 1

1. Start with wheel in uncollapsed form, attached to the wheelchair axle.
2. Have stop watch and all accompanied tools ready.

3. Have participant disassemble the wheel when told to “start”.
4. Start timing.
5. Stop timing when wheel is fully in its collapsed state.
6. Record time.
7. Have participant reassemble the wheel and attach it to wheelchair axle when told to “start”.
8. Start timing.
9. Stop timing when wheel is fully assembled and attached to wheelchair.
10. Record time.
11. Have participant read the provided User Manual for instructions on how to properly assemble and disassemble the wheel.
12. Repeat Steps 1-10 and record the new time.
13. Repeat Steps 1-12 with other participants of various ages.
14. Compare assembly time with benchmark and other collapsible wheels.
15. Visually demonstrate the effectiveness of the provided instructions in User Manual.

TEST 2: Deflection Under Load
Appendix H – pg. 2

1. Attach wheel in uncollapsed form to wheelchair axle.
2. Attach strain gauges to the critical locations:
    a. Rim, midpoint between spokes.
    b. Spoke, wall and face.
3. For 4 – 7 inches above the seat, have the 250-pound human specimen sit into wheelchair in a “plopping” motion.
4. Record strain values.
5. Repeat 10 times.
6. Repeat steps 3 – 5 with 300-pound human specimen.

TEST 3: Terrain Test
Appendix H – pg. 3

1. Attach Collapsible Wheel to wheelchair.
2. Use human specimen of approximately 250 pounds.
3. With the specimen in the wheelchair, have one person push the wheelchair 10 yards on a smooth, flat surface.
4. Have the second person observe and interrogate the Collapsible Wheel as it traverses the surface. The observer will rate the wheels performance on a scale of 1-10 based on these parameters:
    a. Stability
    b. Wobbling
    c. Concentricity
    d. Solidness of Assembly
    e. Deflection / Bending
    f. Fluidity while Moving
    g. Ride comfort
5. At the end of 10 yards, the specimen will turn around and propel himself/herself using the push rims for the returning 10 yards.
6. The second person will observe and interrogate again and take special note of how the user interacts with the push rim.
7. Repeat steps 3-6 with various users of different weight and age.
8. Repeat steps 2-7 with various terrain, such as slopes, gravel, mud, grass, rain, etc.

9. Compare the rating from each test to determine the strengths and weaknesses and whether weight is affecting the performance.

TEST 4: Single Spoke Strength
Appendix H – pg. 4

1. Load one spoke into Tinius Olsen.
2. Zero out dial indicator.
3. Zero out deflection gauge.
4. Load in increments of 50 lb. up to 450 lb.
5. Record the readings at each load increment.
6. Unload device.
7. Repeat steps ‘x’ times for consistency.
8. Plot data using Excel.
9. Compare values to analysis calculation and FEA predictions.

DELIVERABLES

PHYSICAL PROPERTIES EVALUATION

Name: Joe Fischer

Date: 4-10-15

Trial Number: #1

Dimension	Benchmark	Predicted	Actual	Notes
Uncollapsed Height	24.0 in.	24.0 in.	23.5 in.	Different Tire – Easily Adjustable
Uncollapsed Width	24.0 in.	24.0 in.	23.5 in.	
Uncollapsed Depth	4.0 in.	1.0 in.	1.1 in.	Rubber Tire Overhang
Collapsed Height	12.5 in.	10.75 in.	10.375 in.	
Collapsed Width	32.0 in.	11.25 in.	11.250 in.	
Collapsed Depth	4.0 in.	6.0 in.	6.6 in.	
Frontal Area	452.4 in.^{2}	~~71.9 in.^{2}~~ 75.4 in^2	72.3 in^2	
Weight	7.5 lb.	10.9 lb.	10.3 lb	Lighter Rubber Tires?

COLLAPSIBLE WHEEL ASSEMBLY / DISASSEMBLY TEST

Name: Joe Fischer

Date: 4-11-15 – 4-26-15

Trial Number: #1

Participant (#)	Age (years-old range)	Without Instructions: Time (assemble) (seconds)	Without Instructions: Time (disassemble) (second)	With Instructions: Time (assemble) (seconds)	With Instructions: Time (disassemble) (seconds)
1	15-20	5:32.5	3:08.6	5:27.0	2:23.1
2		7:40.3	4:53.0	7:10.7	4:01.8
3		10:03.8	3:58.7	4:40.3	2:41.6
4		8:25.3	4:15.0	6:03.8	3:11.1
5	21-30	8:31.5	5:20.4	4:10.7	5:06.8
6		8:56.1	3:08.5	5:58.0	2.49.7
7		5:21.1	4:13.2	5:09.6	3.18.8
8		6:18.3	2:41.7	3:14.1	2:18.1
9	31-40	5:41.6	4:00.7	5:04.0	2:31.5
10		8:21.2	5:27.2	6:13.7	2:45.0
11		4:33.3	4:16.6	4:37.9	3:17.3
12		5:01.5	3:18.9	4:29:2	2:50.9
13	41-50	6:38.2	3:42.0	5:08.1	2:25.0
14		6:21.9	2:33.3	4:44.2	2:12.9
15		7:48.0	4:19.2	6:01.7	3:50.4
16		10:18.3	6:02.8	6:47.5	4:34.7
17	51-60	6:18.8	3:21.1	4:04.8	2:50.5
18		5:56.1	3:51.6	4:52.2	3:27.6
19		5:42.2	2:50.8	3:38.7	2:52.2
20		8:21.5	4:52.4	5:05.4	4:11.6

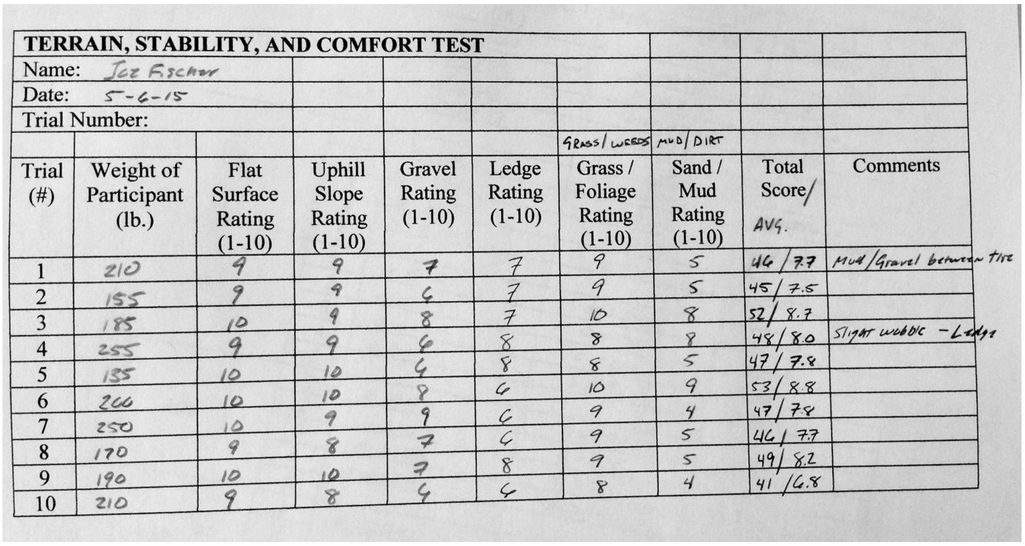
WHEEL DEFLECTION UNDER VARIOUS LOADS

Name: Joe Fischer

Date: 5-2-15

Trial Number: #1

Load (lb.)	Trial (#)	(TIRE RIM) Deflection @ loc. 1 (in.)	(SPOKE) Deflection @ loc. 2 (in.)	(HUB) Deflection @ loc. 3 (in.)
250	1	0.0063	0.0070	0.000
	2	0.0059	0.0071	0.000
	3	0.0061	0.0072	0.000
	4	0.0058	0.0072	0.000
	5			
300	1	0.0082	0.0111	0.000
	2	0.0082	0.0102	0.000
	3	0.0090	0.0108	0.000
	4	0.0107	0.0110	0.000
	5			
350	1	0.0125	0.0212	0.000
	2	0.0137	0.0198	0.000
	3	0.0138	0.0208	0.000
	4	0.0129	0.0190	0.000
	5			
400	1	0.0177	0.0337	0.001
	2	0.0167	0.0322	0.001
	3	0.0176	0.0351	0.001
	4	0.0170	0.0300	0.001
	5			
450	1	0.0200	0.0598	0.001
	2	0.0208	0.0612	0.002
	3	0.0211	0.0611	0.002
	4	0.0211	0.0608	0.002
	5			



TERRAIN, STABILITY, AND COMFORT TEST

Name: Jez Fischer

Date: 5-6-15

Trial Number:

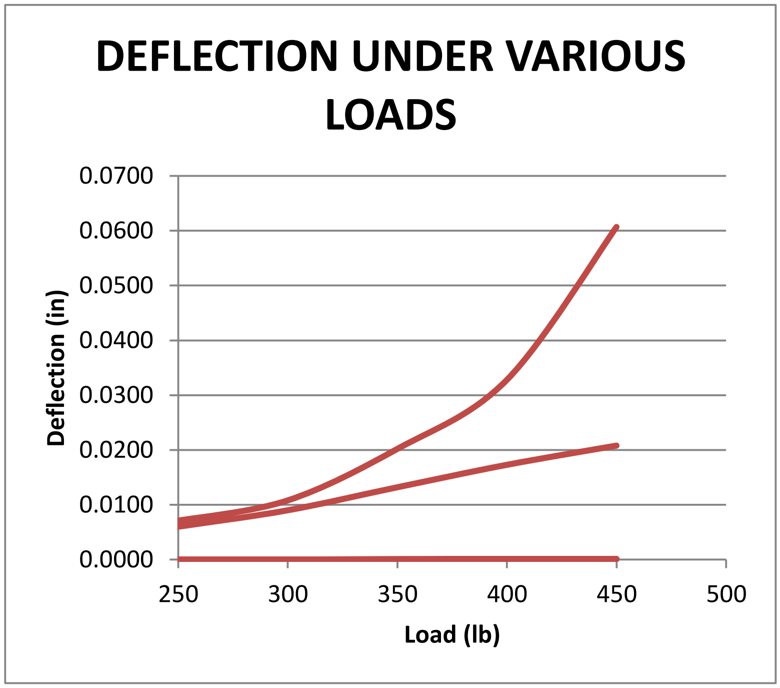
Trial (#)	Weight of Participant (lb.)	Flat Surface Rating (1-10)	Uphill Slope Rating (1-10)	Gravel Rating (1-10)	Ledge Rating (1-10)	GRASS/WEEDS Grass / Foliage Rating (1-10)	MUD/DIRT Sand / Mud Rating (1-10)	Total Score/ AVG.	Comments
1	210	9	9	7	7	9	5	46 / 7.7	Mud/Gravel between tire
2	155	9	9	6	7	9	5	45 / 7.5	
3	185	10	9	8	7	10	8	52 / 8.7	
4	255	9	9	6	8	8	8	48 / 8.0	Slight wobble - Ledge
5	135	10	10	6	8	8	5	47 / 7.8	
6	200	10	10	8	6	10	9	53 / 8.8	
7	250	10	9	9	6	9	4	47 / 7.8	
8	170	9	8	7	6	9	5	46 / 7.7	
9	190	10	10	7	8	9	5	49 / 8.2	
10	210	9	8	6	6	8	4	41 / 6.8	

RESULTS

COLLAPSIBLE WHEEL ASSEMBLY TEST				
participant	assemble 1	disassemble 1	assemble 2	disassemble 2
1	05:32.5	03:08.6	05:27.0	02:23.1
2	07:40.3	04:53.0	07:10.7	04:01.8
3	10:03.8	03:58.7	04:40.3	02:41.6
4	08:25.3	04:15.0	06:03.8	03:11.1
5	08:31.5	05:20.4	04:10.7	05:00.8
6	08:56.1	03:08.5	05:58.0	02:49.7
7	05:21.1	04:13.5	05:09.6	03:13.8
8	06:18.3	02:41.7	03:14.1	02:18.1
9	05:41.6	04:00.7	05:04.0	02:31.5
10	08:21.2	05:27.2	06:13.7	02:45.0
11	04:33.3	04:16.6	04:37.9	03:17.3
12	05:01.5	03:18.9	04:29.2	02:50.9
13	06:38.2	03:42.0	05:08.0	02:25.0
14	06:21.9	02:33.3	04:44.2	02:12.9
15	07:48.0	04:19.2	06:01.7	03:50.4
16	10:18.3	06:02.8	06:47.5	04:34.7
17	06:18.8	03:21.1	04:04.8	02:50.5
18	05:56.1	03:51.6	04:52.2	03:27.6
19	05:42.2	02:50.8	03:38.7	02:52.2
20	08:21.5	04:52.4	05:05.4	04:11.6
AVG	**without instruction**		**with instruction**	
	07:05.6	**04:00.8**	**05:08.1**	**03:10.5**
% IMPROV			**assembly**	**27.6%**
			disassembly	**20.9%**

The collapsibility test revealed that most people could not assemble the wheel within the 5-minute goal or disassemble it within the 3-minute goal. The average time for assembly was 7:05.6 and 4:00.8 for disassembly. The reason the assembly takes longer that expected is because of the welding alignment issues that occurred during the construction phase. This problem forced the wheel sections to have to be assembled in a particular order, ultimately adding time to the assembly process. Another area that can be improved is the hub screw. Replacing the hub fasteners with quick-release bolts would reduce the assembly and disassembly time by over a minute. What helped significantly is the instruction manual. After letting the user read the instructions for 5-10 minutes, the assembly time improved 27.6% and closer to the requirement goal of 5 minutes. This is also true for the disassembly time of 3:10.5 on average.

DEFLECTION UNDER VARIOUS LOADS TEST		
location	load	avg. deflection (4 trials)
	(lb)	(in)
RIM	250	0.0060
	300	0.0090
	350	0.0132
	400	0.0173
	450	0.0208
SPOKE (h)	250	0.0071
	300	0.0108
	350	0.0202
	400	0.0328
	450	0.0607
SPOKE (v)	250	0.0000
(buckling)	300	0.0000
	350	0.0001
	400	0.0001
	450	0.0001
HUB	250	0.0000
	300	0.0000
	350	0.0000
	400	0.0001
	450	0.0001



Test 2 was important for testing the maximum weight capacity and deflection requirements. According to the requirements, a pair of wheels should be able to support a 250-pound load and deflect no more than 0.050 inches in any location. The test at each weight load was performed 4 times and the deflection at each location was recorded. The average deflection of the 4 trials is shown in the table on the left. At only one instant the deflection exceed 0.050 inches. When loaded at 450 pounds, the horizontal spoke deflected 0.060 inches. Even though 450 pounds is far greater than the 250-pound requirement, according to the FEA and Safety factor of 2.0, the spoke should not have deflected more than 0.050 inches. However, this does make sense since this test used impact force to simulate how the wheels would actually be loaded in real-world scenarios whereas the FEA only calculated static loads.

TERRAIN, STABILITY, AND COMFORT TEST									
trial	weight	flat surface	uphill slope	gravel	ledge	grass/foliage	mud/dirt	total score	percent grade
1	210	9	9	7	7	9	5	46	76.7%
2	155	9	9	6	7	9	5	45	75.0%
3	185	10	9	8	7	10	8	52	86.7%
4	255	9	9	6	8	8	8	48	80.0%
5	135	10	10	6	8	8	5	47	78.3%
6	200	10	10	8	6	10	9	53	88.3%
7	250	10	9	9	6	9	4	47	78.3%
8	170	9	8	7	6	9	5	44	73.3%
9	190	10	10	7	8	9	5	49	81.7%
10	210	9	8	6	6	8	4	41	68.3%
Grading Criteria:									
2 = Superb. No problems. Performs perfectly.									
1 = Average. Doesn't perform perfectly but still within parameters.									
0 = Bad. Performs below average and below expectations.									
Grading Categories:									
1. Ride Comfort / Smoothness									
2. Stability / Rigidity									
3. Concentricity									
4. Deflection / Bending / Warping									
5. Ease of Use									

This test was important for ensuring the Collapsible Wheel performed to the standards of a traditional wheel. It is important that this new wheel does not cause any discomfort and is able to maintain functionality over various terrain just as well as a traditional wheel.

According to the traditional wheel test (top table), the average rating was 84.7%. The average rating for the Collapsible Wheel test (bottom table) was 78.7%. This difference was a result of the Collapsible wheel having some "wobble" due to its profile being thinner. There was also some concern on the gravel, grass, and dirt courses due the gaps between the tire sections getting clogged and causing discomfort and instability.

PHYSICAL PROPERTIES EVALUATION				
Name: Joe Fischer				
Date:				
Trial Number:				
Dimension	**Benchmark**	**Predicted**	**Actual**	**Notes**
Uncollapsed Height	24.0 in.	24.0 in.	23.5 in.	Different tire height than expected
Uncollapsed Width	24.0 in.	24.0 in.	23.5 in.	
Uncollapsed Depth	4.0 in.	1.0 in.	1.1 in.	Rubber tire overhang
Collapsed Height	12.5 in.	10.75 in.	10.375 in.	
Collapsed Width	32.0 in.	11.25 in.	11.250 in.	
Collapsed Depth	4.0 in.	6.0 in.	6.6 in.	
Frontal Area	452.4 in.^{2}	75.4 in.^{2}	72.3 in.^{2}	
Weight	7.5 lb.	10.9 lb.	10.3 lb.	Lighter rubber than SolidWorks model? Pushrim is a less dense metal than expected?

It was also important to measure the final dimensions and properties of the actual product to compare with the predicted design values, the benchmark, and other competitive products. The actual dimensions came very close to the predicted values, especially considering some of the difficulties experienced in the construction phase.

BUDGET

PART SUPPLIERS

The budget is located in **Appendix D**. Materials and parts for this project were purchased from many different locations. The aluminum stock came from www.onlinemetals.com. The spring latches had to be a certain size to fit within the wheel rim so they were purchased from www.electrausa.net, an online company that focuses exclusively on hinges. These latches had to be purchased earlier than expected due being back-ordered. The screws used for the hinges were a standard size so they were purchased at Stein's Hardware, a local hardware store in Yakima, WA. The hex bolts could not be found at a local supplier since a specific thread length was needed so they were ordered from www.amazon.com. Using Amazon also reduced the cost slightly since they support a variety of suppliers with competing prices. Other fasteners were purchased through www.fastenal.com. The solid rubber tire was obtained along with the push rim, and ball bearing from a contact that works at a local retirement home called Better Living Retirement Homes. The aluminum tire rim was purchased from a local cycling shop in Yakima, WA called Yakima Valley Cycling. The rim was purchased instead of machined because the machinery needed to create the complex shape of the tire rim is not obtainable within the scope of this project.

ESTAMATED TOTAL COST

According to the budget in **Appendix D**, the estimated cost of this project will be $162.07. When this project was first conceived it was estimated that the budget would be $200 to $300. Using scrap parts from the local retirement home saved about $100.00. Online suppliers were also thoroughly compared to find the best price (including shipping) for the same quality of material. As predicted, the largest cost will be the material stock at about $70.00. It was difficult to find spring latches that were small enough to fit on the spokes. On top of that, the most cost effective latches found were sold out for multiple months so latches of a different size have to be slightly modified in order to fit this project.

FUNDING SOURCE

The funding for this project will be out of the pocket of the engineer. This includes materials, purchased parts, construction, and testing. Though not directly funded by the previously stated retirement home, it is important to note that Better Living Retirement Homes assisted this project by donating crucial parts that benefitted the budget and schedule of this project.

SCHEDULE

The schedule is located in **Appendix E**. The schedule format used is a Gantt chart. This chart identifies specific tasks and goals, the amount of time allocated for completing each task, the actual time it took to complete the task, and a visual representation of when the task will take place. The estimated time for this project is 256 hours and includes design, analysis, construction, assembly, testing, and optimizing. This will take place over the 9 month scholastic year from September 2014 to June 2015. The amount of time to complete each task is an estimation in order to gage a total, to keep on task, and to compare the actual time required to complete each task and the whole project altogether. Design, analysis, drawings, and the related proposal started in September 2014 and ended December 2014. More time was required for design and analysis than initially predicted. This is due to the number of redesigns and related analysis to compare different designs. Construction of the project will start with the ordering of parts in December 2014 and will be completed by March 2015. Some parts such as the spring latches needed to be ordered early because of their availability and estimated delivery time. A larger portion of time will be allotted for ensuring the precise dimensions of the spokes and the amount of welding that needs to occur. The testing phase for this project will start in March 2015 and end June 2015.

PROJECT MANAGEMENT

HUMAN RESOURCES

The engineer is responsible for all tasks including design, analysis, acquisition of materials, construction, and testing. Central Washington University professors, Charles Pringle, Craig Johnson, and Roger Beardsley, assisted with feedback on design, analysis, and formatting. Central Washington University lab technician, Matthew Burvee, assisted with machine set up and construction processes. Jenny Ford of Better Living Retirement Homes assisted by donating particular parts used in this project.

PHYSICAL RESOURCES

This project requires the use of a manual or CNC lathe for turning custom parts. A vertical milling machine and/or CNC mill will be requires for certain tasks such as the spoke dimensions and the keyways. A vertical drill press is needed for drilling holes. A band saw will be needed for cutting material stock to the accurate length before machining. Other miscellaneous resources include a threaded tap, vise, press, and grinder. All these physical resources can be found in the machine shop of the Hogue Technology Building, room 107, at Central Washington University. Lab time will need to be set up in order to allow for enough time to complete the project. This should follow the guidelines of the schedule in **Appendix E**. This project also requires welding, particularly aluminum welding. This project will require the use of the TIG welding machine located in the Hogue foundry, room 132, at Central Washington University. Lastly, the parts of the project will require a small amount of storage throughout the duration of the construction phase and testing phase. This will mostly take place in the Hogue lockers but may also require machine shop space, foundry space, and senior project room space depending on what process is being applied and what phase of completion the project is at.

SOFT RESOURCES

The CAD program used for this project was SolidWorks 2014. SolidWorks was also used for FEA in a portion of the analysis. MDSolids 3.5 was also used as an analysis tool for stresses and displacement of some parts to compare with hand calculations. Both SolidWorks and MDSolids were also used to calculate complex shapes that could not be calculated by hand. These soft resources are accessible from the Hogue CAD lab at Central Washington University and from a personal computer.

FINANCIAL RESOURCES

The financial resource for this project is the engineer. The engineer is responsible for locating and purchasing all required purchase parts, materials, tools, and equipment.

DISCUSSION

DESIGN EVOLUTION

This project underwent a few redesigns. This project started as a series of sketches to determine how the wheel would be separable and how the wheel would interlock. It was always the intention to analyze different designs to see how well each iteration would handle the proposed requirements of this project. The first design analyzed was a 4-piece, 4-spoke design, which was called Version 1.0. After some deflection analysis on the rim, an intermediate spoke was adding between the 90-degree spokes. This 4-piece, 8-spoke design was Version 1.1. This also allowed for a location to add a push rim. Next, a 6-piece, 6-spoke design, Version 2.0, was analyzed. This design decreased the frontal area and the overall weight, which are two of the main areas of optimization.

The method in which the wheel sections attach and interlock also underwent a few redesigns. The initial locking method in Version 1.0 used cylindrical rings attached to each wheel section to mate to the hub. See **Figure 3.** This design was dismissed for impractical construction required to make the part and for clearance issues with the welding. Also at this version, a pin was used to lock the spokes in place to ensure the tire stay inline. This method was also redesigned for future versions since keeping track of removable pin for a portable wheel seemed impractical. For Version 2.0, the method in which the wheel pieces attached to the hub was redesigned to bolt on to a hub plate welded to the axle hub. Also, there was a bored out area added to the spoke bases to allow the hub plate fit inside the spoke bases when attached. This reduced the amount of shear stress on the bolts.

For all versions 1.1 and on, a keyway was added between each of the spoke halves. This helped with alignment, strengthening the spokes by doubling their cross sectional area, and resisting buckling by interlocking the two halves. The keyway design drove the design geometry for the spoke halves. In order to be machinable and also have enough wall thickness, the spokes must be rectangular column/beam. For Version 2.0, a third and final method of locking the parts together was the spring loaded latch. This replaced the pin lock in Version 1.0. This method ensures the rim and tire are locked into place after the spokes are interlocked with the keyway. This also allows for easy assembly and disassembly of the wheel pieces.

In total, there are three ways the wheel sections lock together. Bolting the spoke bases to the hub resists unwanted movement in all directions towards the bottom of the spoke. The keyway resists unwanted movement towards the left and right, perpendicular to the spoke and also any movement inward along the negative z-axis throughout the length of the spoke. Lastly, the spring loaded latch resists unwanted movement in the outward direction along the positive z-axis towards the rim and tire.

PROJECT RISK ANALYSIS

There is a fair amount of risk associated with this project. Since this is wheelchair wheel, its primary users will be elderly and/or disabled. If the wheel fails or breaks when in use it could cause considerable injury. There is also risk if the push rim breaks and the wheelchair user loses control since the wheel is also designed to be self-operational. These issues were addressed a few different ways. First, a safety factor of 2.0 was applied to all points of interest in the wheel meaning all parts were designed to withstand double required applied load of 250 pound for the pair of wheels. This is good since it given extra strength for overweight users and situations where the wheel encounters extra impact such as dropping off a curb or ledge or dropping a user into the seat of the wheelchair. It was also important to analysis endurance strength since wheelchairs are used for many hours at a time and for many years before being replaced. It is also important that the user of the wheel understands how to use the wheel properly. If the wheel sections are not locked into place properly, there is a much higher probability of failure and, more importantly, injury. A User Manual with instructions for proper use and assembly was made to supplement the Assembly Efficiency Test in the Testing Procedures Section. These instructions will come with the Collapsible Wheel to ensure the user knows how to assemble the wheel and reduce the chance of injury.

SUCCESS

The success of this project is based on whether the wheel solves the engineering problem proposed, meets the requirements set, functions as the function statement describes, and outperforms the benchmark. This will depend on the final dimensions and physical properties of the wheel after the construction phase in Quarter 2. This will also depend on the testing conducted in Quarter 3.

For this project to be successful, the collapsible wheel must perform as intended, meaning it must function as a structural wheel for a wheelchair while a person is using it. It must also collapse as intended and be storable as one cohesive unit. See **Figure 9** for the Checklist Table of requirements and how they company to the benchmark.

REQUIREMENT	TEST PERFORMED	BENCHMARK (Maddak Morph Wheel)	PREDICTION	ACTUAL	NOTES & IMPROVEMENTS & CONCLUSION
Is a standard 24-in. wheelchair wheel & can collapse to less than half of original frontal area	measurement	24 in. dia 452.4 in.^{2} area	24 in. dia 75.4 in.^{2} area	23.5 in. dia 72.3 in.^{2} area	Slightly undersize due to tire height.
Can perform as a standard wheelchair wheel and handle everyday situations over various terrain	TEST 3 – Terrain Test	N/A	Handles all terrain tested	7.9/10 average rating	Performs well on most terrain. Gaps between tire sections could be reduced as to not catch gravel, mud, grass, etc.
Contains a functional push rim of the correct size	Construction & TEST 3	18 in. ± 2 dia	18-in. pushrim	18-in. pushrim & optional pushrim handlebars	Two options. Would benefit from quick-release fasteners
Support a 250-lb. load without failing or deflecting more than 0.050 in. in any location	TEST 2 – Deflection Under Load Test	Rated at 250-lb. weight capacity	250-lb. weight capacity w/ 2.0 Safety Factor	Max @ 250lb = 0.0072" Max @ 450lb = 0.0612"	Area of greatest deflection was the tire rim which was not constructed
The wheel must weigh less than or equal to 10 lb.	measurement	7.5 lb.	10.9 lb.	10.3 lb.	Limited by material choice & budget
The wheel can be collapsed and assembled within 3 and 5 minutes, respectively	TEST 1 – Assembly Efficient Test	N/A	3 min. collapse 5 min. assembly	3:10 collapse 5:08 assembly	Can be improved with quick release fasteners & better build quality
Comes with user instruction manual for proper use and assembly	TEST 1	Has Instructions Online	Will improve assembly time	Assembly 27.6% faster, Disassembly 20.9% faster	Significantly improved assembly time

Figure 9: Requirement Checklist & Comparison

NEXT PHASE

There are some things that could be improved upon for this project but were not implemented due to budget, resources, and/or time. First, to make the wheel lighter weight, a glass filled nylon could be used. This was analyzed for this project but was not used due to the cost of the material and the lack of resources needed to machine the material which keeping the dimensions within the required tolerance. Given a larger budget, more time, and access to more resources, the wheel sections of this project could be injection molded using 30% glass-filled nylon to reduced weight while still keeping a safety factor of 2.0.

Next, it would make the collapsible wheel more convenient to design a push rim that could collapse along with the frame instead of just being removable thus eliminating extra parts in which the user must keep track of. This also applies to the hub bolts. The number of bolts was decreased from 12 to 6, but it would be even more convenient to design a quick release so no bolts were needed.

It would be beneficial to have a method in which the wheel sections lock together when collapsed. This could be implemented with snaps or magnets. It would also be beneficial to design a way for the wheel to attach to the wheelchair other than the axle for storage options.

This design of this project could also be utilized in the collapsible bicycle market. With a slight modification to the axle, this collapsible wheelchair wheel could function as a collapsible bicycle wheel, granted the push rim is removed.

CONCLUSION

This project underwent many redesigns to try to create a collapsible wheelchair wheel that could compete with other collapsible wheels on the market. The emphasis was on reducing the frontal area at the cost of depth but, also, keeping structural integrity. As wheelchair frames get more compactable and lightweight, the dimensions of a storable wheelchair will be hindered by the diameter of the wheels. The final design is a 24" x 1" 6-piece, 6-spoke collapsible wheel with two styles of push rim. This projects design reduces the frontal area to 71.9 square inches, a reduction of 83.4%, when collapsed. Compared to the benchmark Morph Wheel frontal area of 452.4 square inches, this design has 84% less frontal area. In terms of dimensions, this design is 11.25" x 10.75" when collapsed, where the Morph Wheel is 32" x 12.5". In terms of optimization, more than just the frontal area was considered. The geometry, dimensions, and material of the wheel frame all had to be analyzed to meet the maximum load, deflection, weight, and functionality requirements. Furthermore, the total cost of this project (minus man-hours for construction) is around $170. The Morph Wheel by Maddak retails for $950 for a pair. This project's design would cost about $340 for a pair before the retail mark-up.

ACKNOWLEDGEMENTS

A special thanks to the Central Washington University MET staff, Professor Charles Pringle, Professor Roger Beardsley, Dr. Craig Johnson, and Mr. Matthew Burvee for the support, assistance, advice, and overall help throughout this project. Thank you CWU faculty, specifically for the Hogue Technology Building, for providing the space and tools needed to design, construct, and test this project. Thank you to Jenny Ford and the Better Living Retirement Home staff for donating parts and providing useful wheelchair information and experience. A special thanks to Patrick "Lee" Hansen for assistance and training required for the welding process during the construction phase.

Sincerely,

Joe Fischer

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[2.] www.matweb.com
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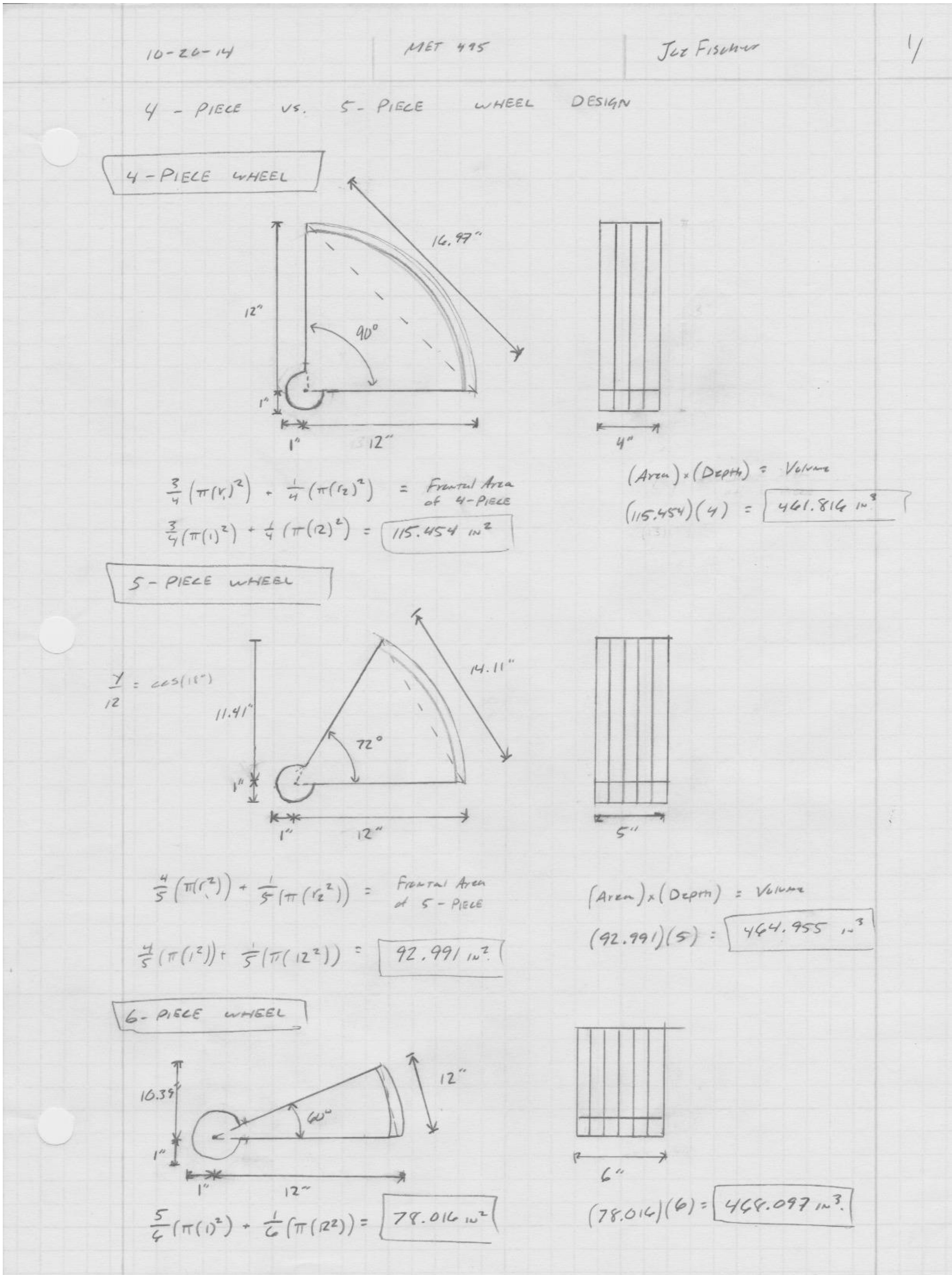
[7.] Modern Welding, 11th Edition, A. Althouse, C. Turnquist, W. Bowditch, K. Bowditch, M. Bowditch
[8.] Conversation: Wheelchair problems and concerns. Ford, Jenny. Better Living Retirement Home staff.

APPENDIX A – Analyses



ANALYSIS 1: Simple geometry is performed to determine frontal area and depth of a 4-, 5-, and 6-spoked wheel design.

10-22-14 | MET 495 | Jez Fischer | 1/

SPOKE FORCES

GIVEN: Total weight on Wheel Pair = 250 lbf (Person weight + Chair weight)

FIND: Reactant Forces

SOL'N:

Force per wheel = $250\ \text{lbf}/2 = 125\ \text{lbf}$

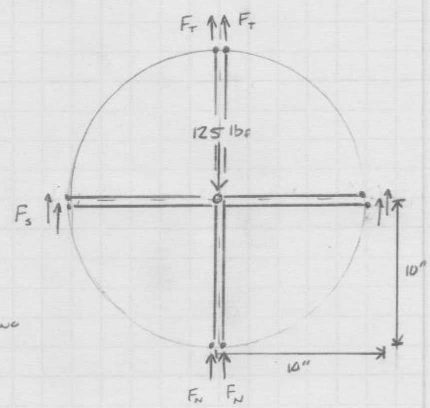
$\Sigma F_y = 0 = 2F_T + 2F_N + 4F_s - 125\ \text{lbf}$

$F_T = F_N = F_s$

$125 = 8F_N$

$\boxed{F_N = 15.625\ \text{lbf}}$

∴ 15.625 lb of tension on top two spokes and 15.625 lb of compression on bottom two spokes.



4 - Spoke @ 0°

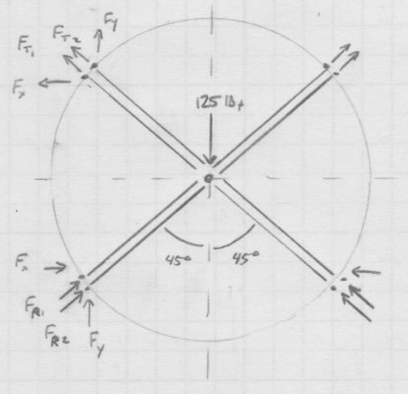
$\Sigma F_y = 0 = -125 + 8F_y$

$F_y = 15.625\ \text{lbf}$

$F_R = \sqrt{(15.625)^2 + (15.625)^2}$

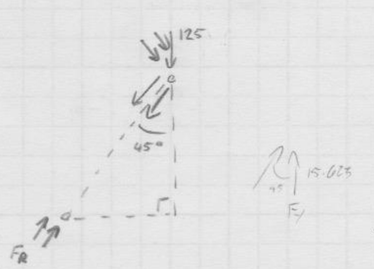
$\boxed{F_R = 22.097\ \text{lbf}}$

∴ 22.097 lb of tension and compression radially from the 125-lb load.



4- SPOKE @ 45°

∴ MAX FORCE IN 45° POSITION. USE 22.097 lbf FOR STRESS/STRAIN ANALYSIS.



ANALYSIS 2: Determined forces for a 4-piece collapsible wheel in two orientations.

10-23-14 | MET 495 | Jer Fischer | 1/

SPOKE FORCES WITH INTERMEDIATE SPOKES

GIVEN: 4-piece wheel design, extra spoke per piece, 250 lbf force total load

FIND: Reaction forces

SOLN:

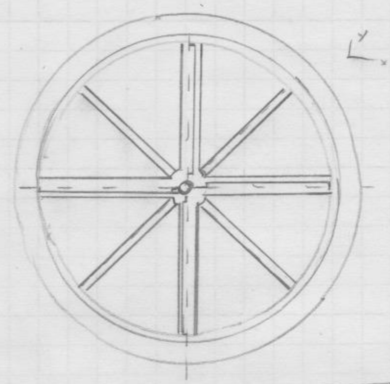
$$\Sigma F_y = 0 = -125 + 12F_y$$

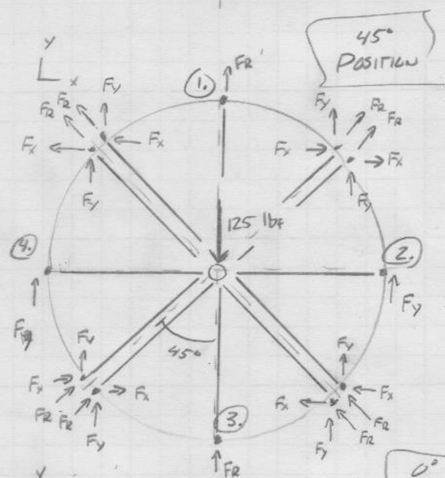
$$F_y = 125/12 = 10.417 \text{ lbf}$$

∴ 10.417 lbs of radial force at points 1, 3.

$$F_R = \sqrt{(10.417)^2 + (10.417)^2} = 14.732 \text{ lb}$$

∴ 14.732 lb of radial force on the 45° spokes.



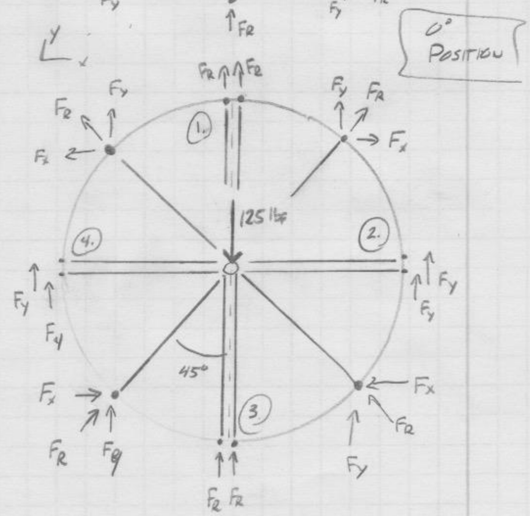


@ 0° POSITION –

10.417 lb of radial force at points 1, 3.

+

14.732 lb of radial force at 45° spokes



∴ Reduction from:

15.625 lbs to 10.417 lbs at 0° position

+

22.097 lb to 14.732 lb at 45° position.

33.3% improvement in load distribution.

ANALYSIS 3: Determined forces in a 4-piece wheel design with an intermediate spoke in two orientations.

10-30-14 | MET 495 | Jez Fischer | 1

GIVEN: Radial Forces in Previous Analysis

FIND: Tension + Compression Stresses of Spokes

SOLN:

A, B:

$$\sigma_{AB} = \frac{P}{A} = \frac{(10.417)\ lb}{\left((.75)(.25)+(.25)(.25)+(.50)(.25)\right) in^2}$$

$$\boxed{\sigma_{AB} = 27.779\ psi\ (tension)}$$

F, E:

$$\boxed{\sigma_{FE} = \sigma_{AB} = 27.779\ psi\ (compression)}$$

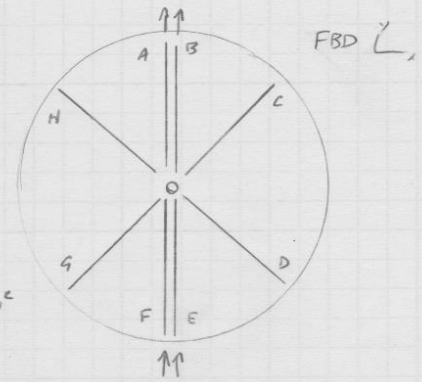
C, H:

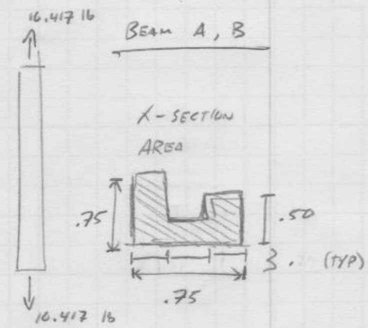
$$\sigma_{C,H} = \frac{(14.732)\ lb}{(.50)(.375)\ in^2}$$

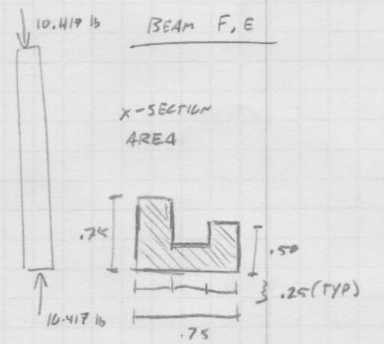
$$\boxed{\sigma_{C,H} = 78.571\ psi\ (tension)}$$

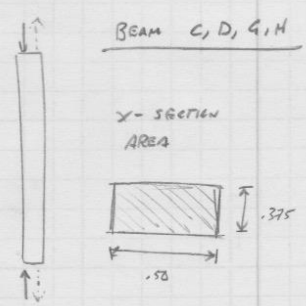
D, G:

$$\boxed{\sigma_{D,G} = \sigma_{C,H} = 78.571\ psi\ (compression)}$$









ANALYSIS 4: Determined tension and compression stresses in spokes.

4-PIECE 8-SPOKE DESIGN

SPOKE LENGTH	10
SAFETY FACTOR	2
LOAD	125
COLUMN FACTOR	0.5

A 6061-T6	
TENSILE YIELD	40000
BEARING YIELD	56000
ELASTIC MOD.	10000000
DENSITY	0.0975

NYLON 6 (20%)	
TENSILE YIELD	23200
FLEX YIELD	34100
TENSILE MOD	1040000
FLEX MOD	1020000
DENSITY	0.0462

NYLON 6 (10%)	
TENSILE YIELD	16700
FLEX YIELD	24700
TENSILE MOD	696000
FLEX MOD	638000
DENSITY	0.0434

SPOKE	FORCE	MOMENT	STRESS	ADJ YIELD (AL)	ADJ YIELD (NY-20)	ADJ YIELD (NY-10)	SAFE? (AL)	SAFE? (NY-20)	SAFE? (NY-10)
A	0.00	1250.00	10000.00	20000.00	11600.00	8350.00	YES	YES	NO
B	176.78	883.88	9899.49	20000.00	11600.00	8350.00	YES	YES	NO
C	125.00	0.00	166.67	20000.00	11600.00	8350.00	YES	YES	YES
D	176.78	883.88	9899.49	20000.00	11600.00	8350.00	YES	YES	NO
E	0.00	1250.00	10000.00	20000.00	11600.00	8350.00	YES	YES	NO
F	-176.78	883.88	8956.69	20000.00	11600.00	8350.00	YES	YES	NO
G	-125.00	0.00	166.67	28000.00	11600.00	8350.00	YES	YES	YES
H	-176.78	883.88	8956.69	20000.00	11600.00	8350.00	YES	YES	NO

	EFF LENGTH	CRIT LOAD (AL)	CRIT LOAD (NY20)	CRIT LOAD (NY10)	SAFE? (AL)	SAFE? (NY-20)	SAFE? (NY-10)
G	5.00	-138791.31	-14434.30	-9659.88	YES	YES	YES

b1 =	**1**	
		h1 =
MAIN		**0.75**
SPOKE	(A,C,E,G)	
b2 =	**1.5**	
INTERMEDIATE		**h2 =**
SPOKE	(B,D,F,H)	**0.25**

ANALYSIS 5: Excel spreadsheet for 4-piece wheel design using aluminum and nylon materials.

SPOKE STRESSES   MET 495   Jer Fischer   1

GIVEN: A 6061-T6 , 125 lb load @ AXLE
S.F. = 2 ,

FIND: base + width of spokes

SOLN:

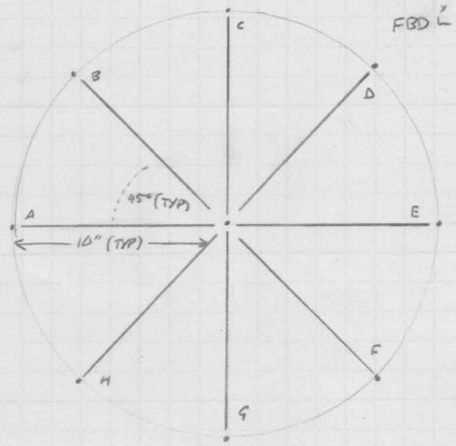
Mat'l Data : Tensile Yield = 40000 psi
Bearing Yield = 56,000 psi
Mod. Elastic = 10,000 psi $\times 10^3$
density = 0.0975 lb/in³

Eq. : $\sigma = P/A$

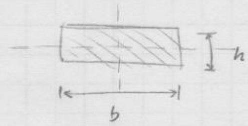
$P_{CR} = \frac{\pi^2 E I_N}{L^2}$, N=4 (double fixed)

$I_x = \frac{bh^3}{12}$

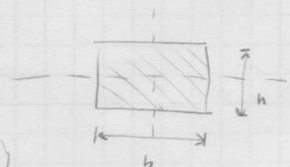
$\sigma = \frac{Mc}{I}$



X-SECTION B, D, F, H :

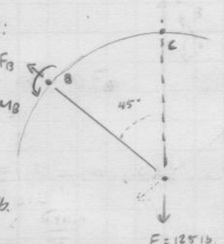


X-SECTION C, E, G, A :



TENSION SIDE:

@ B :



$\Sigma F_y = 0 = -125 + 2\cos(45) F_B$

$F_B = 176.78$ lb.

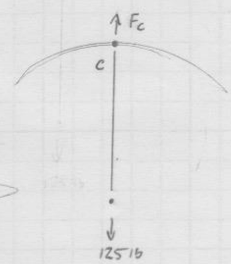
$\Sigma M_B = 0 = M_B - (125)\cos(45)(10)$

$M_B = 883.88$ lb·in.

TENSION/BENDING STRESS:

$$\sigma_B = \frac{P}{A} + \frac{M}{S} = \boxed{\frac{(176.78)}{bh} + \frac{(883.88)}{\left(\frac{h\,b^2}{6}\right)} < \frac{\sigma_{YIELD}}{SF}}$$

@ C :



$\Sigma F_y = 0 = -125 + F_C$

$F_C = 125$ lb

TENSION STRESS:

$$\sigma_C = \frac{P}{A} = \boxed{\frac{(125)}{bh} < \frac{\sigma_{YIELD}}{SF}}$$

ANALYSIS 6: Force and stress calculations used for the basis of ANALYSIS 5. (Aluminum 6061-T6)

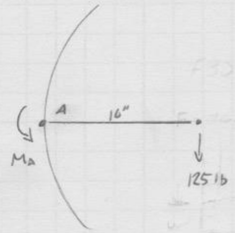
SPOKE STRESSES - CON'T

2/

@ A:

$\Sigma F_y = 0 = -125 + F_A$

$F_A = 125$



$\Sigma M_A = 0 = M_A - 125(10)$

$M_A = 1250 \text{ lb} \cdot \text{in}$

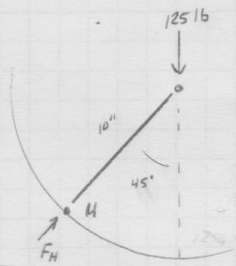
BENDING STRESS:

$$\boxed{\sigma_A = \frac{M}{S} = \frac{(1250)}{\left(\frac{h\,b^2}{6}\right)} < \frac{\sigma_{YIELD}}{SF}}$$

@ H:

$\Sigma F_y = 0: -125 + F_H \cos(45)$

$F_H = 176.78 \text{ lb}$



$\Sigma M_H = 0 = M_{H0} - (125)\cos(45)(10)$

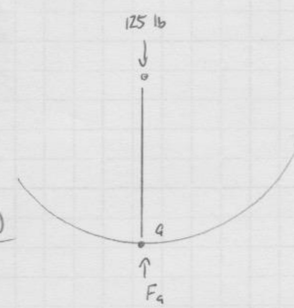
$M_H = 883.88 \text{ lb} \cdot \text{in}$

COMPRESSION / BENDING STRESS:

$$\sigma_H = -\frac{P}{A} + \frac{M}{S}$$

$$\boxed{= -\frac{(176.78)}{bh} + \frac{(883.88)}{\left(\frac{h\,b^2}{6}\right)} < \frac{\sigma_{YIELD}}{SF}}$$

@ G:



$\Sigma F_y = 0 = -125 + F_G$

$F_G = 125 \text{ lb}$

Buckling Force:

$$P_{CR} = \frac{(n)\pi^2 EI}{L^2} = \frac{(4)(\pi^2)(10\times10^3)(b\,h^3/12)}{(10)^2}$$

$$\boxed{\sigma_G = \frac{125}{bh} < \frac{\sigma_{YIELD}}{SF} \quad \text{AND} \quad 125 \text{ lb} < P_{CR}}$$

ANALYSIS 7: Force and stress calculations used for the basis of ANALYSIS 5. (Aluminum 6061-T6)

SPOKE STRESSES | MET 495 | Joe Fischer | 1/

GIVEN: Nylon 6/6 - Dry 10% Glass — Nylon 6/6 - Dry 20% Glass

Mat'l Data:	Tensile Yield:	16700 psi	–	23,200 psi
	Tensile Mod:	696 ksi	–	1040 ksi
	Flex. Strgth:	24,700 psi	–	34,100 psi
	Flex. Mod:	638 ksi	–	1020 ksi
	Density:	0.0434 lb/in³	–	0.0462 lb/in³

BENEFITS OF NYLON:

STRENGTHS

- Strong (tensile + modulus)
  - Below PEEK, LCP, PET.
- Low friction
- Creep resistance

WEAKNESSES

- Absorbs water (tolerancing)
- Machining

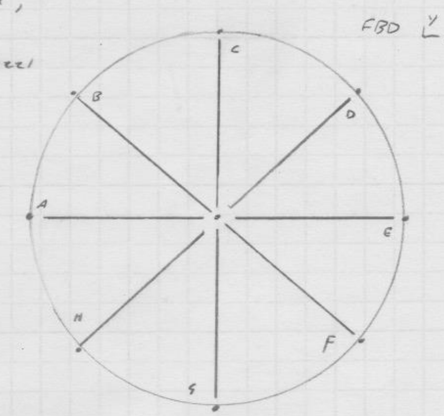
ANALYSIS 8: Nylon mechanical properties obtained from matweb.com for ANALYSIS 5 spreadsheet.

STRAIN / DEFLECTION - 4-PIECE (NYLON 6/6 20%)

GIVEN: NYLON 6/6 20%, 125 lb load,
Stresses from "ANALYSIS 5"

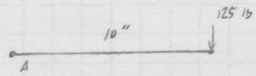
FIND: Deflection at beams in wheel

SOLN:



MAT'L DATA: Tensile Yield = 23,200 psi
Tensile Mod. = 1640 ksi
Flex. Strength = 34,100 psi
Flex. Mod. = 1020 ksi
Density = 0.0462 lb/in³

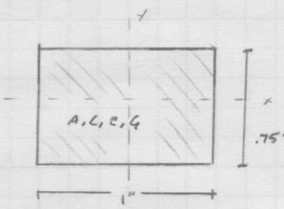
@ A :



[MOTT TABLE A14-2]

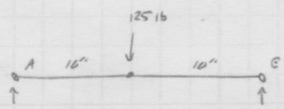
$$y_{max} = \frac{-PL^3}{3EI}$$

$$= \frac{(125\ lb)(10\ in)^3}{3(1640 \times 10^3)\frac{lb}{in^2}\left(\frac{.75 \times 1.0^3}{12}\right)} = 0.641\ in$$



[NOTE: Assuming spoke A supports 125 lb load alone.]

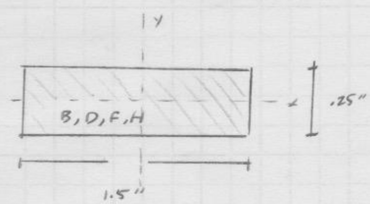
@ A, E :



[MOTT TABLE A14-1]

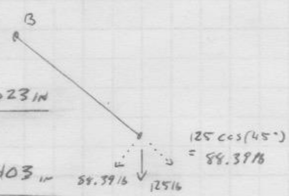
$$y_{max} = \frac{-PL^3}{48EI}$$

$$= \frac{(125)(10)^3}{48(1640 \times 10^3)\left(\frac{.75 \times 1^3}{12}\right)} = 0.040\ in$$



By analyzing both A and E supporting the load, the deflection is ≅ 16 x less.
∴ Nylon 6/6 20% should have no problem fulfilling the deflection requirement of 0.100 in.

@ B :



$$\delta_x = \frac{FL}{EA} = \frac{(88.39)(10)}{(1640 \times 10^3)(.25 \times 1.5)} = 0.0023\ in$$

$$Y_{max} = \frac{PL^3}{3EI} = \frac{(88.39)(10)^3}{3(1640 \times 10^3)\left(\frac{.25 \times 1.5^3}{12}\right)} = 0.403\ in$$

$$\delta_{TOTAL} = \sqrt{\delta_x^2 + \delta_y^2} = \sqrt{0.0023^2 + 0.403^2} = 0.403\ in \Downarrow$$

[NOTE: Assuming spoke B supports 125 lb load alone.]

ANALYSIS 9: Calculations for beam deflection in 4-piece nylon wheel design.

11-9-14 | MET 475 | Jon Fischer | A-9

DEFLECTION – 4-PIECE (NYLON 6/6 ZEY.) – continued

@B :

[with 8 spokes, assuming load is distributed evenly → $F = \frac{125}{8} = 15.625$ lb.]

$$\delta_x = \frac{(15.625\cos(45))(10)}{(1040\times10^3)(.75\times1)} = \underline{0.0001416 \text{ in}}$$

$$Y_{max} = \frac{(15.625\cos(45))(10)^3}{3(1040\times10^3)\left(\frac{.75\times1^3}{12}\right)} = \underline{0.0567 \text{ in}}$$

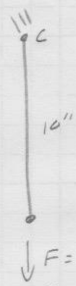
$$\delta_{TOTAL} = \sqrt{(.1416\times10^{-3})^2 + (0.0567)^2}$$

$$\delta_{TOTAL} = 0.0567 \text{ in}$$

more likely solution

@C:

$$\delta = \frac{FL}{EA} = \frac{(125)(10)}{(1040\times10^3)(.75\times1)} = \underline{0.0016 \text{ in}}$$



$F = 125$ – Assuming column takes whole load

$F = 15.625$ – Assuming load is evenly distributed

0.0016 in < 0.100 in.

Deflection in vertical column from requirement load is ok even with full load acting on that column only.

ANALYSIS 10: Calculations for beam deflection in 4-piece nylon wheel design.

6-PIECE 6-SPOKE DESIGN

SPOKE LENGTH	10	**A 6061-T6**		**NYLON 6/6 (20%)**	
SAFETY FACTOR	2	TENSILE YIELD	40000	TENSILE YIELD	23200
LOAD	125	BEARING YIELD	56000	FLEX YIELD	34100
COLUMN FACTOR	0.5	ELASTIC MOD.	10000000	TENSILE MOD	1040000
		DENSITY	0.0975	FLEX MOD	1020000
				DENSITY	0.0462

SPOKE	FORCE	MOMENT	STRESS	ADJ YIELD (AL)	ADJ YIELD (NY-20)	SAFE? (AL)	SAFE? (NY-20)
A	0.00	1250.00	10000.00	20000.00	11600.00	YES	YES
B	108.25	625.00	5144.34	20000.00	11600.00	YES	YES
C	108.25	625.00	5144.34	20000.00	11600.00	YES	YES
D	0.00	1250.00	10000.00	20000.00	11600.00	YES	YES
E	-108.25	625.00	4855.66	20000.00	11600.00	YES	YES
F	-108.25	625.00	4855.66	20000.00	11600.00	YES	YES

b =	1
A =	0.75
S =	0.125
h =	0.75

ANALYSIS 11: Excel spreadsheet analyzes stress in 6-piece 6-spoke wheel design of two material candidates. Similar to ANALYSIS 5.

11-12-14 | MET 495 | Joe Fischer | A-12

GIVEN: 6-PIECE WHEEL DESIGN, 125 lb load @ axle, S.F. = 2, A 6061-T6

FIND: base + width of spokes

SOLN:

Mat'l Properties:

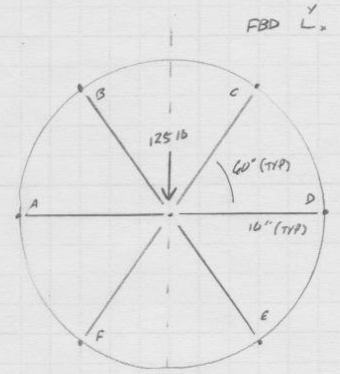
Tensile Yield : 40000 psi

Bearing Yield : 56000 psi

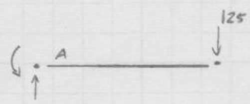
Mod. Elastic : 10×10^6 psi

density : 0.0975 lb/in³

FBD



@ A:



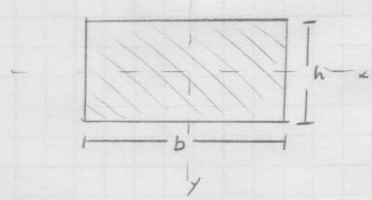
$\sigma_A = \frac{M_A}{S}$

$M_A = 125(10) = 1250$ lb-in.

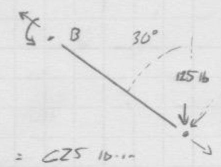
$S = \frac{hb^2}{6}$

$$\boxed{\sigma_A = \frac{1250}{\left(\frac{hb^2}{6}\right)} < \frac{\sigma_{yield}}{S.F.}}$$

X-SECTION



@ B:



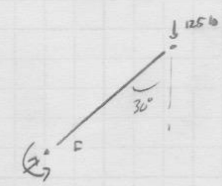
$\sigma_B = \frac{M_B}{S} + \frac{P_B}{A}$

$M_B = 125 \sin(30)(10) = 625$ lb-in

$P_B = 125 \cos(30) = 108.25$ lb

$$\boxed{\sigma_B = \frac{625}{\left(\frac{hb^2}{6}\right)} + \frac{108.25}{(hb)} < \frac{\sigma_{yield}}{S.F.}}$$

@ F



$\sigma_F = \frac{M_F}{S} \pm \frac{P_0}{A}$

$M_F = 125 \sin(30)(10)$
$= 625$ lb-in

$P_F = -125\cos(30) = -108.25$

$$\boxed{\sigma_F = \frac{P_F}{A} - \frac{M_F}{S} = \frac{108.25}{(hb)} - \frac{625}{\left(\frac{hb^2}{6}\right)} < \frac{\sigma_{yield}}{S.F.}}$$

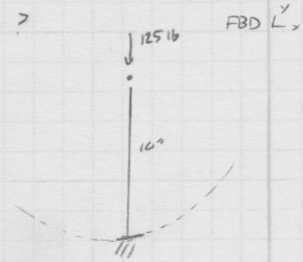
ANALYSIS 12: Stress calculations for 6-piece 6-spoke wheel design. Set up for ANALYSIS 11 spreadsheet.

11-14-14 | MET 495 | Joe Fischer | A-13

Buckling – 6 – spoke

GIVEN: 125 lb load, SF = 2.0, 6-spoke design, A 6061-T6

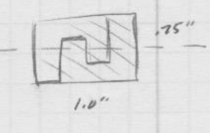
FIND: Does Allowable Load surpass actual load?



SOLN:

$$C_c = \sqrt{\frac{2\pi^2(E)}{S_y}} = \sqrt{\frac{2\pi^2(10\times10^6)}{(40\times10^3)}} = 70.2$$

$$\text{Slender Ratio} = \frac{KL}{r_{min}} = \frac{KL}{\left(\sqrt{I/A}\right)} = \frac{\overset{\text{fixed}}{(0.5)(10)}}{\sqrt{\left(\frac{1\times.75^3}{12}\right)/(1)(.75)}}$$



$$= 23.1$$

NOTE: 70.2 > 23.1

C_c > Slender Ratio $\therefore$ $\boxed{\text{Short Column Analysis}}$

$$P_{CR}\,(\text{short}) = A S_y\left[1 - \frac{S_y\,(KL/r)^2}{4\pi^2 E}\right]$$

$$= (1\times.75)(40\times10^3)\left(1 - \frac{(40\times10^3)(23.1)^2}{4\pi^2(10\times10^6)}\right) = \underbrace{\boxed{28{,}378 \text{ lb}}}_{\text{CRITICAL}}$$

$$P_{ALLOW} = \frac{P_{CR}}{SF} = \frac{28398\text{ lb}}{2} = \underbrace{\boxed{14189\text{ lb}}}_{SF=2}$$

CHECK SF = 3 :

$$P_{ALLOW} = \frac{28378}{3} = \underbrace{\boxed{9457\text{ lb}}}_{SF=3}$$

9459 < 125 lb $\therefore$ column will not buckle when in a vertical orientation.

ANALYSIS 13: Critical buckling force when spoke is in compressed vertical position for 6-piece, 6-spoke design..

11-18-14	MET495	Tor Fischer	A-14

GIVEN: 125 lb applied force, Al 6061-T6, 10" length, .75 x 1.0 spoke.

FIND: deflection

SOLN:

FBD

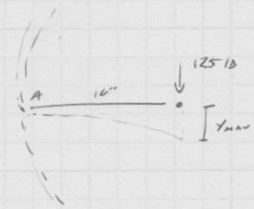


TABLE A14-2:

$$Y_{max} = \frac{-PL^3}{3EI}$$

$$Y_{max} = \frac{-(125)(10^3)}{3(10\times10^6)\left(\frac{1\times.75^3}{12}\right)} = \boxed{0.118 \text{ in}}$$

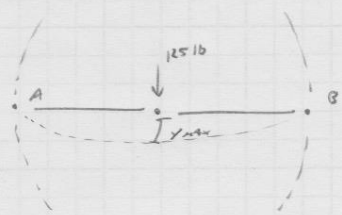
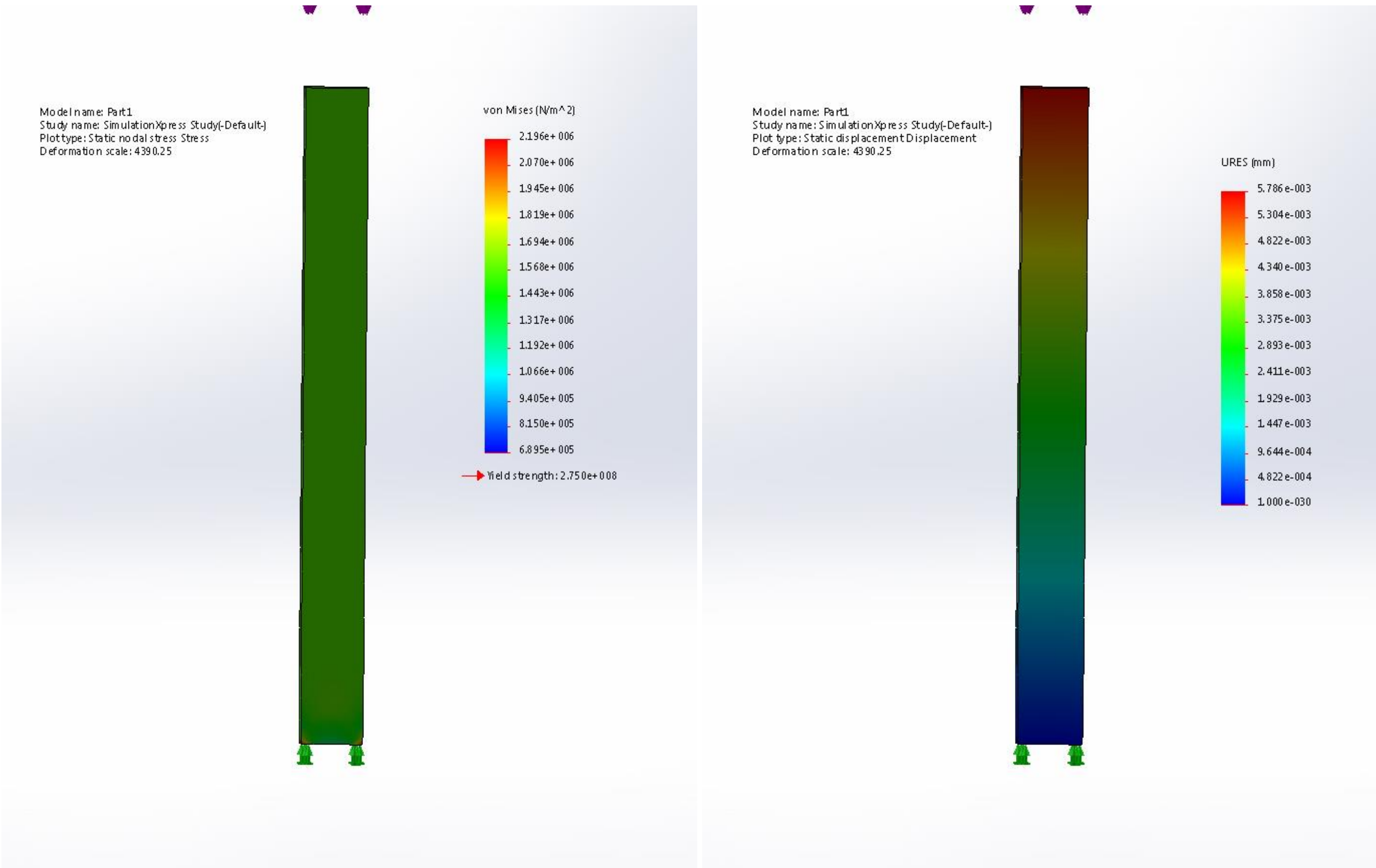


TABLE A14-1:

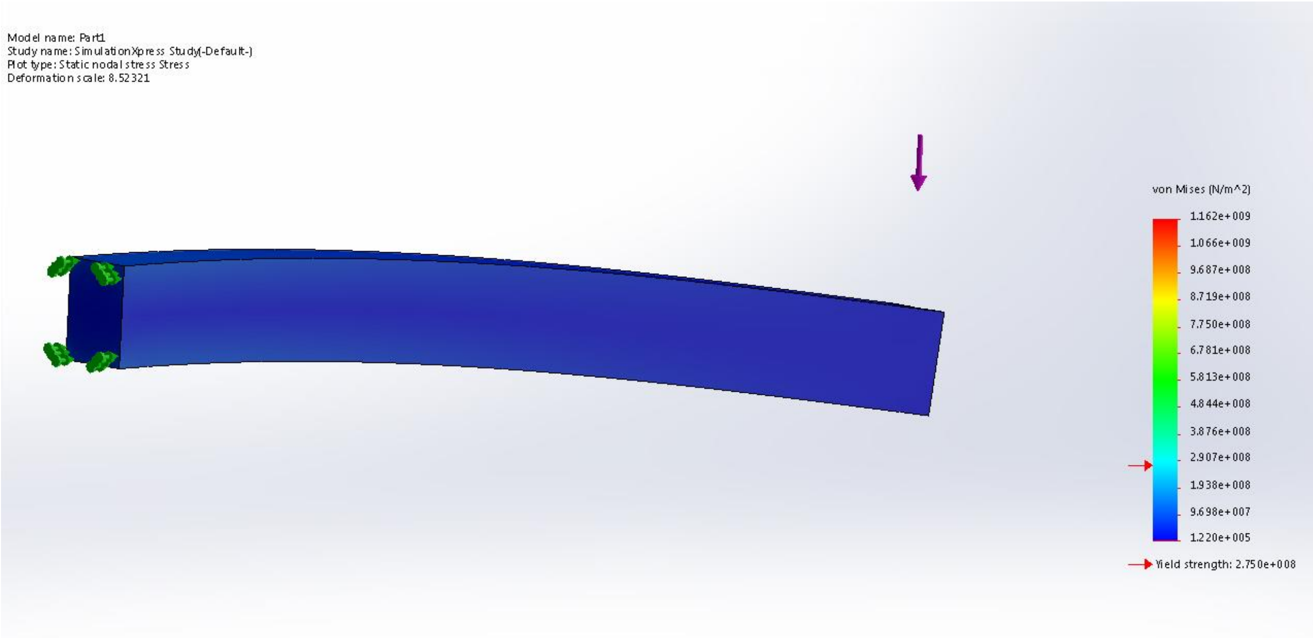
$$Y_{max} = \frac{-PL^3}{48EI}$$

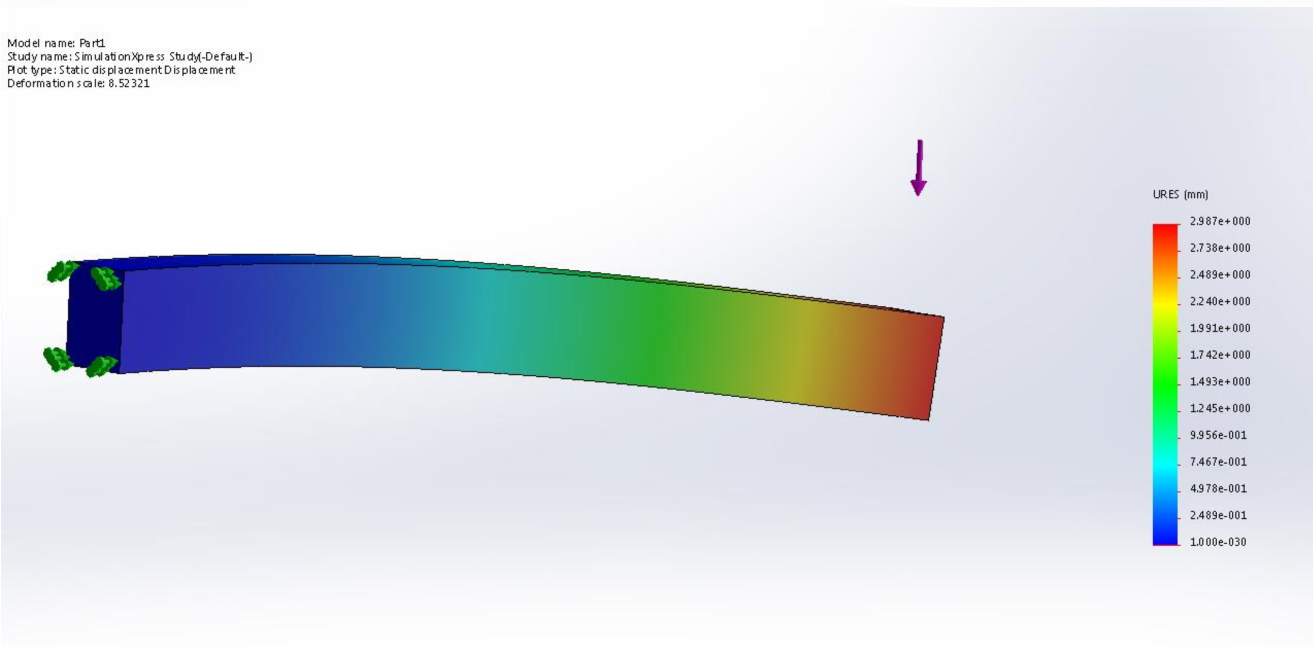
$$Y_{max} = \frac{-(125)(10^3)}{48(10\times10^6)\left(\frac{1\times.75^3}{12}\right)} = \boxed{0.007 \text{ in.}}$$

ANALYSIS 14: Difference in deflection based on number of spokes and location.

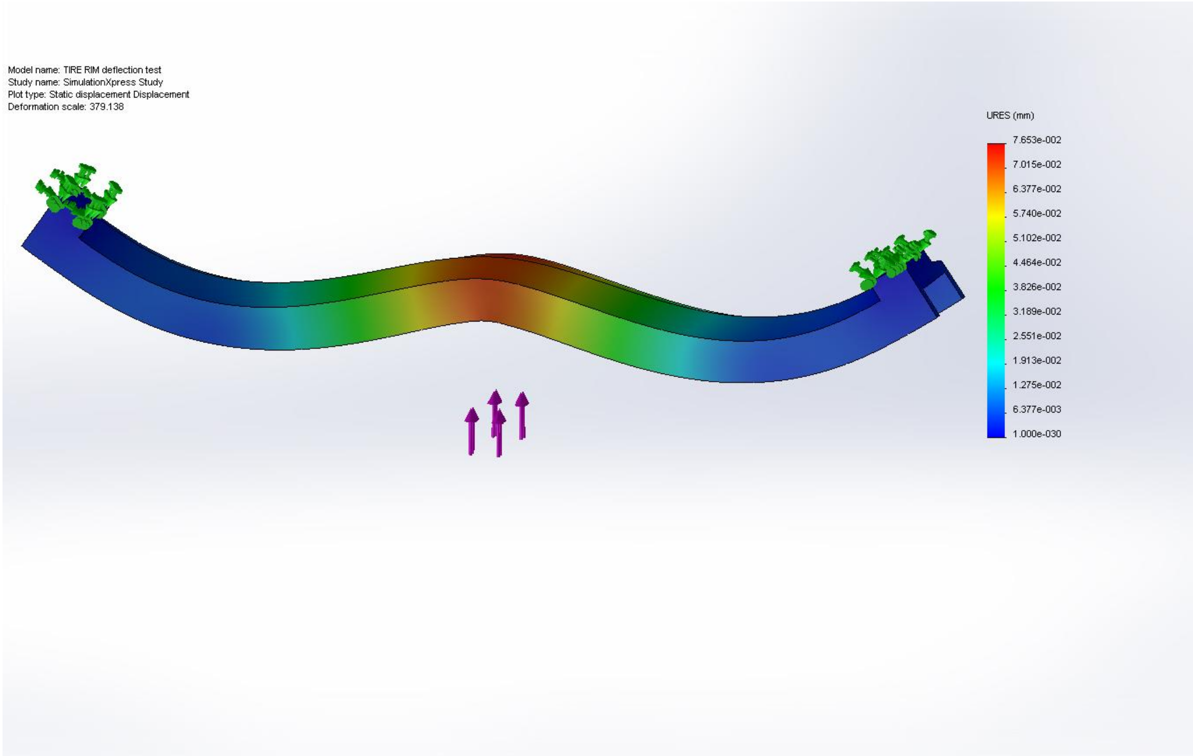


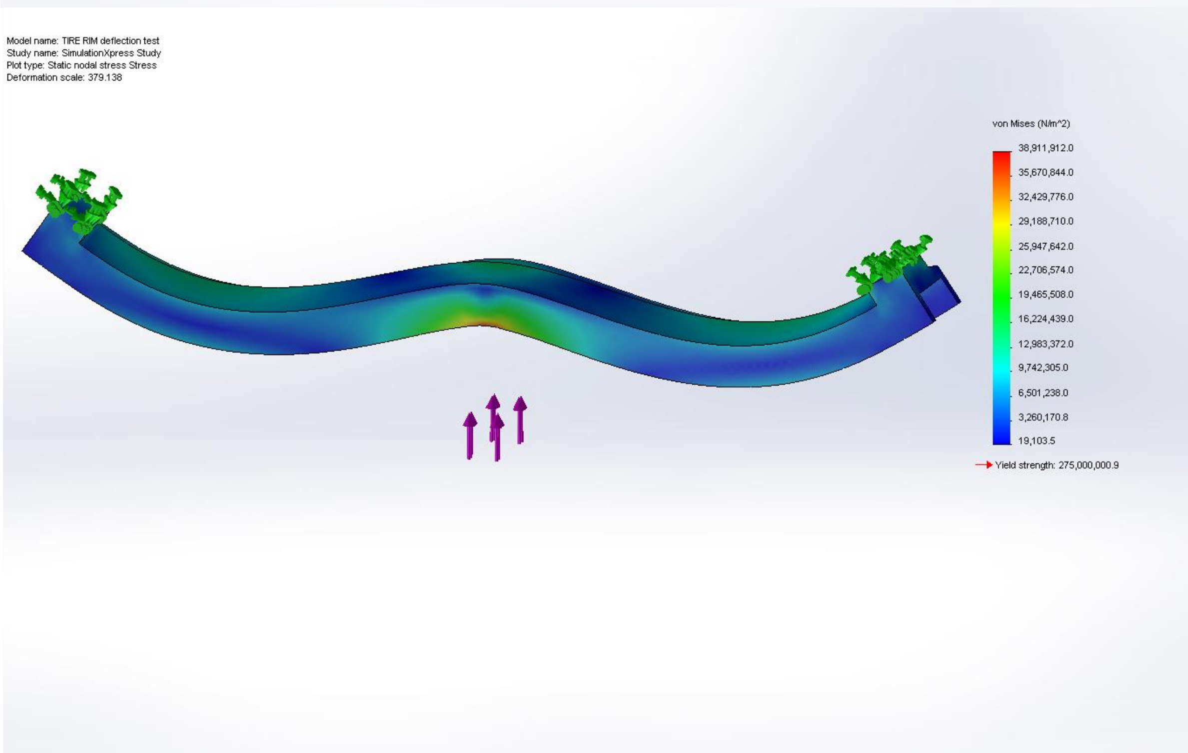
ANALYSIS 15: SolidWorks FEA on vertical column for 6-spoke design. Stress (left) and Deformation (right).



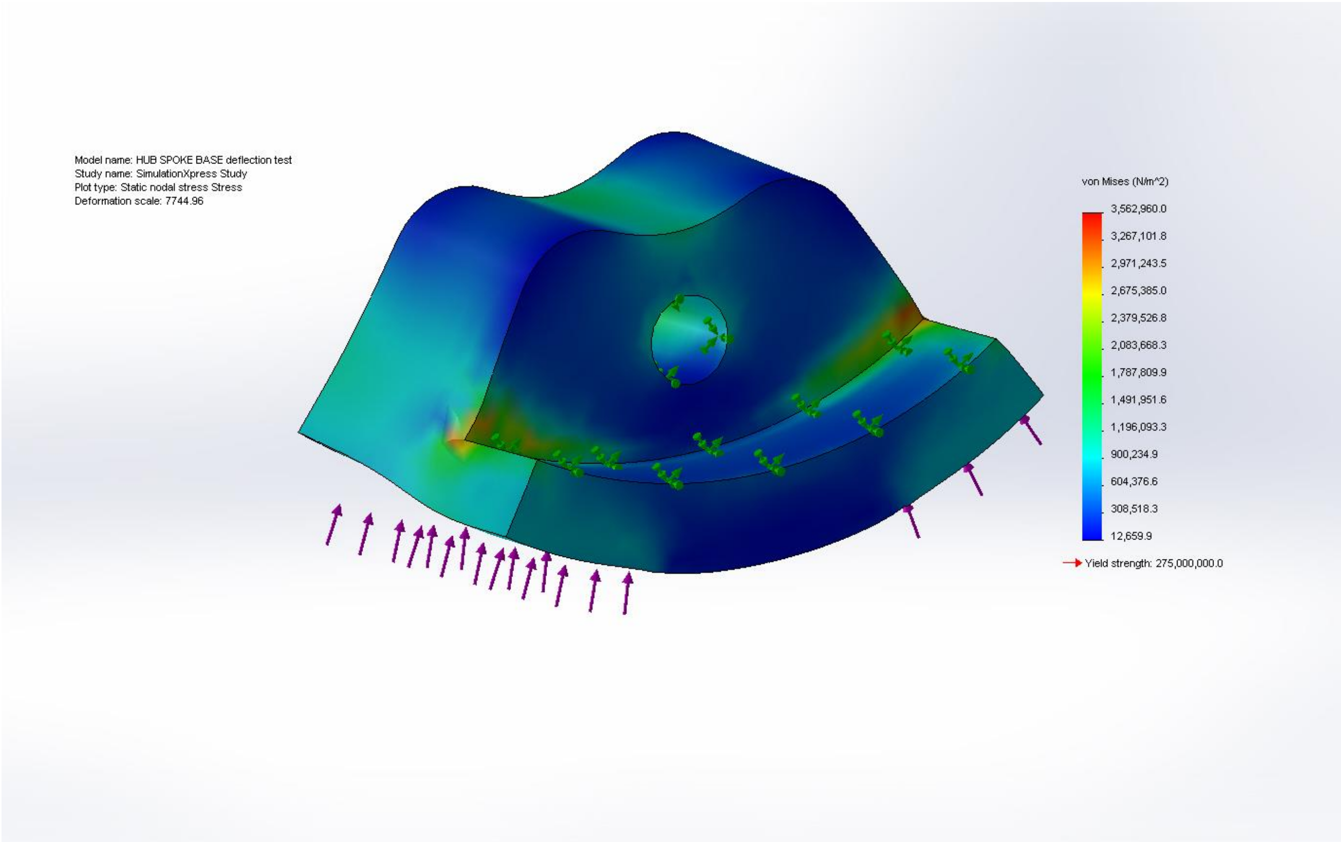


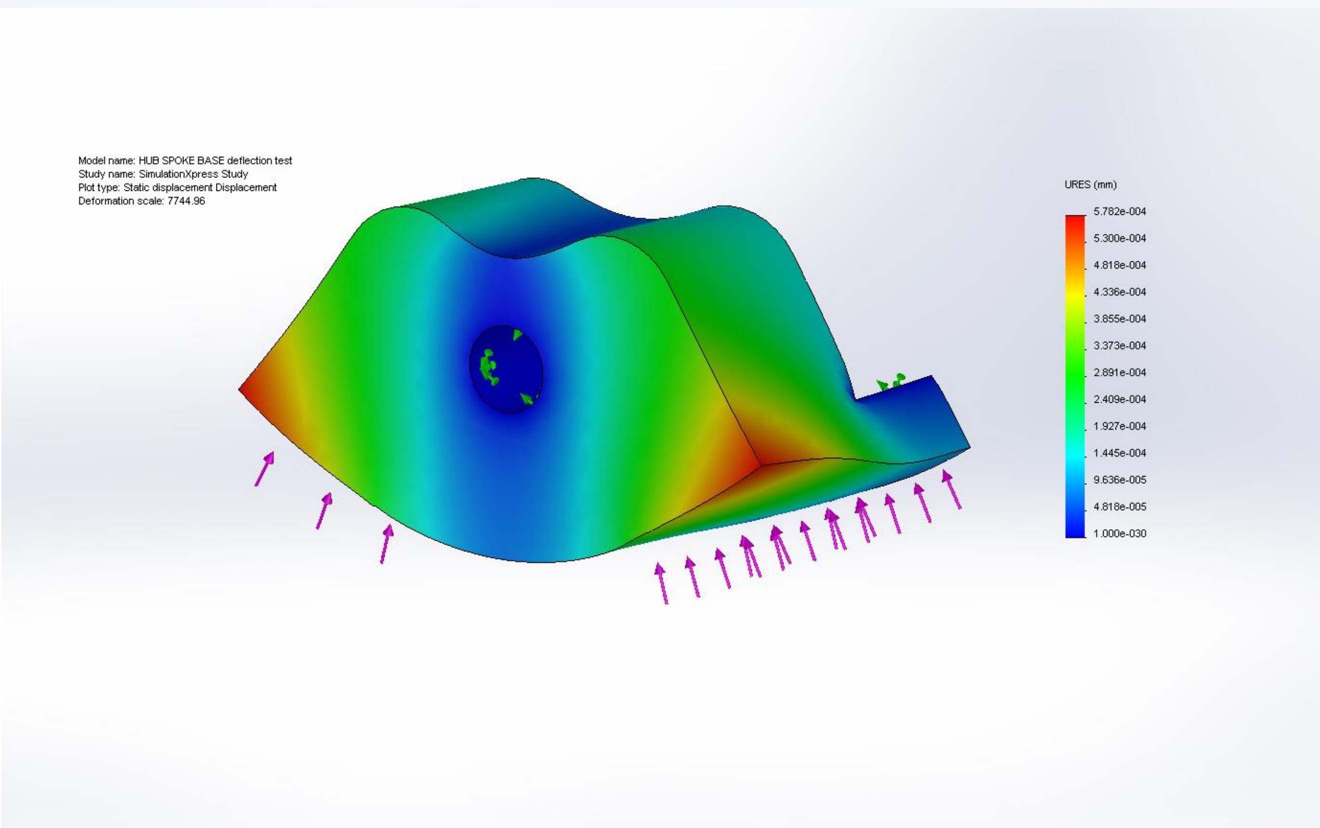
ANALYSIS 16: SolidWorks FEA on horizontal beam of 6-spoke design. Stress (top) and Deformation (bottom)



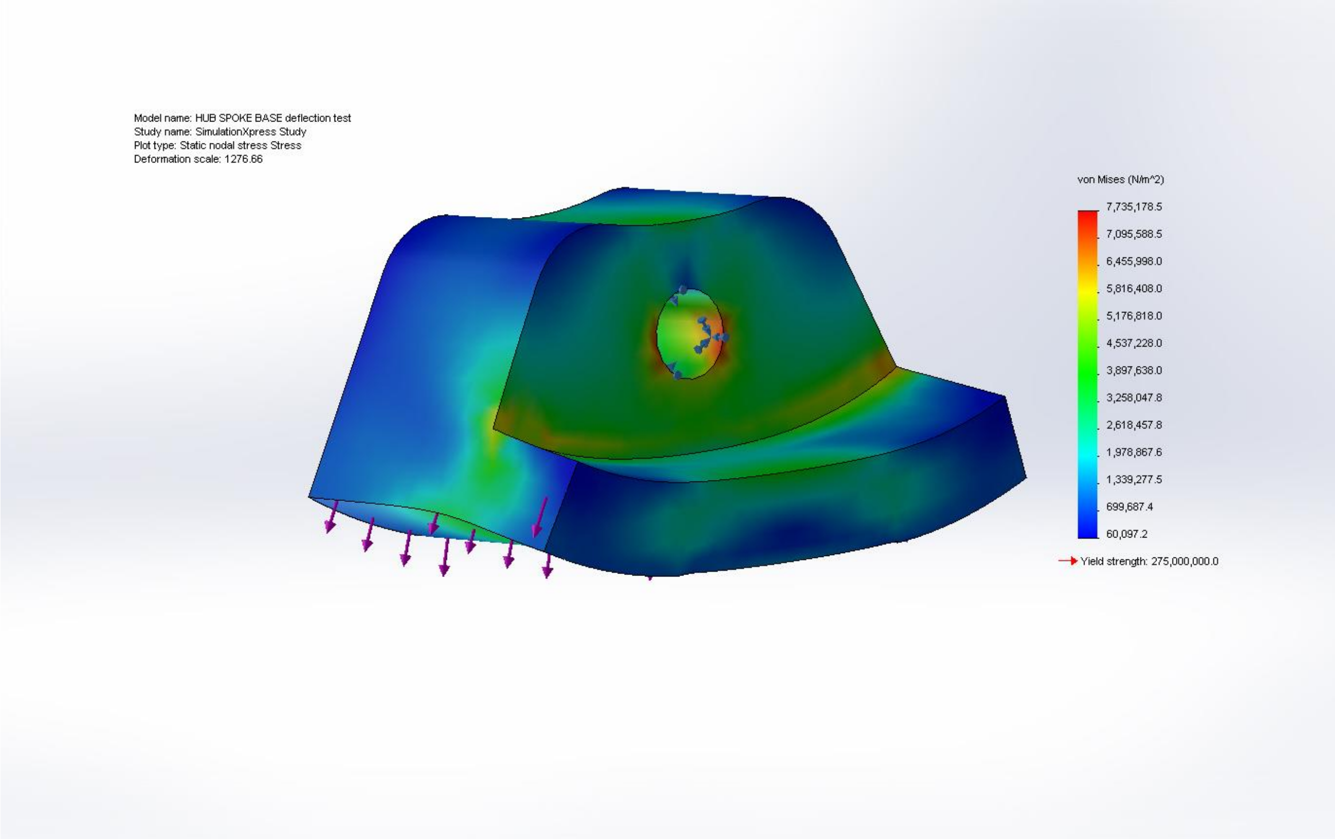


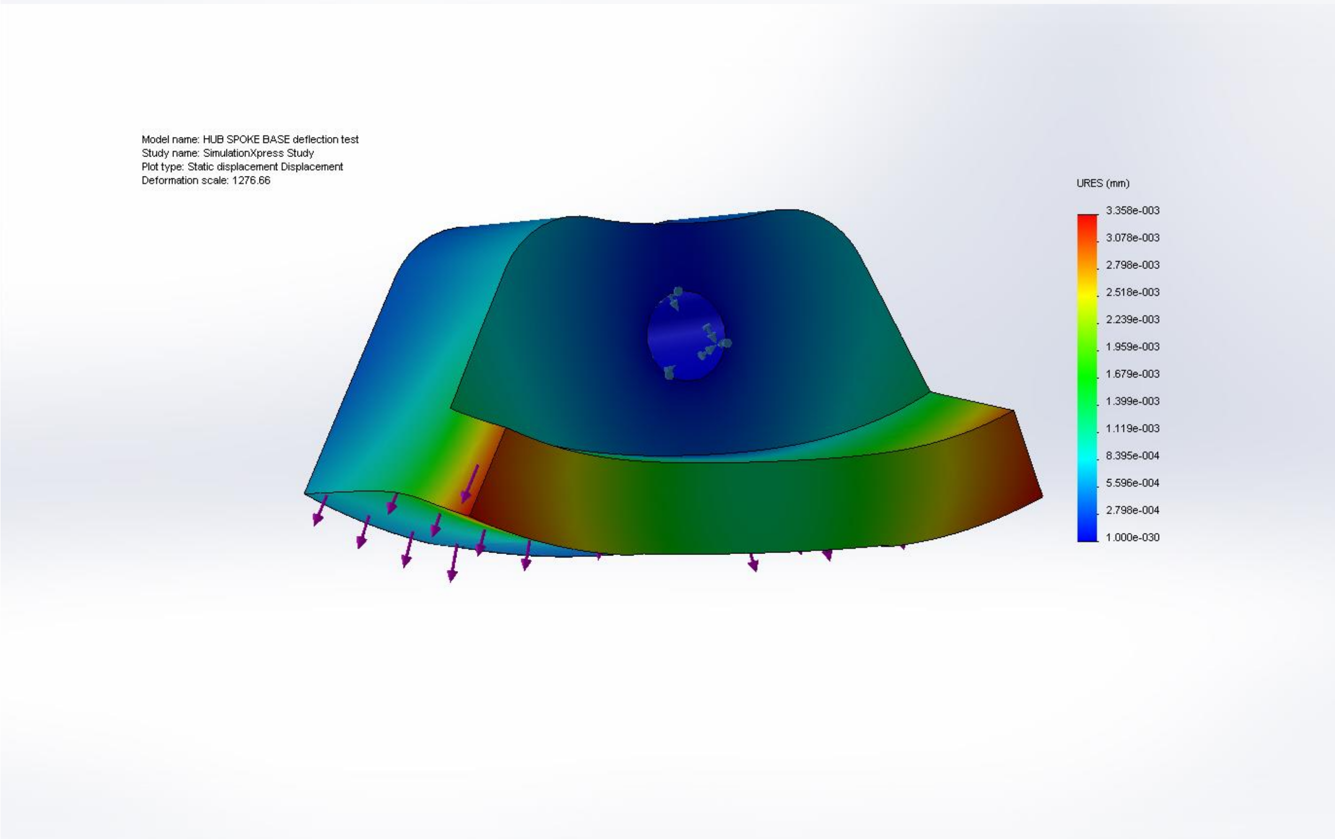
ANALYSIS 17: Solidworks FEA on tire rim section. Stress (top) and Deflection (bottom).





ANALYSIS 18: SolidWorks FEA of hub spoke base in compression. Stress (top) and Displacement (bottom).





ANALYSIS 19: SolidWorks FEA of hub spoke base in tension. Stress (top) and Displacement (bottom).

11-19-14 | MET 495 | Joe Fischer | A-20

Material Fatigue / Endurance

GIVEN: A 6061-T6, 125 lb load.

FBD:

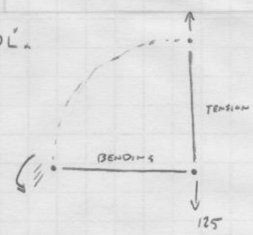
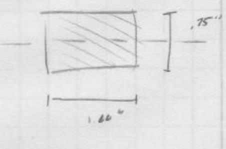


TABLE 5-1 : $S_u = 45{,}000$, S_N (fatigue) $= 20{,}000$, Curve Slope $b = -0.102$

Actual Endurance Strength



$S'_N = S_N C_m C_{st} C_R C_s$

C_m: wrought $\rightarrow \underline{1.0}$

C_{st}: bending $\rightarrow \underline{1.0}$

axial $\rightarrow \underline{0.9}$

C_R: 0.99 reliability $\rightarrow \underline{0.81}$

C_s: @ $.75 \times 1 \rightarrow D_e = 0.808\sqrt{.75} = 0.70 \rightarrow C_s = \left(D/0.3\right)^{-0.11} = \underline{0.71}$

$\therefore \quad S'_N = (20000)(1.0)(1.0)(.81)(.71) = \boxed{11{,}502 \text{ psi (bending)}}$

$S'_N = (20000)(1.0)(0.9)(.81)(.71) = \boxed{9{,}201.4 \text{ psi (axial tension)}}$

5-17: GOODMAN METHOD (fluctuating Stresses for Ductile Material)

$\sigma_{min} = \dfrac{125}{(1 \times .75)} = 166.67$ psi

$\sigma_{max} = \dfrac{125(10)}{\left(\dfrac{1 \times .75^2}{6}\right)} = 13{,}333.33$ psi

$\sigma_m = \dfrac{13333 + 166.67}{2} = 6750$ psi

$\sigma_A = \dfrac{13333 - 166.67}{2} = 4583.33$ psi $\Rightarrow$ $\boxed{\text{Fig. 5-7: @ } \sigma_A = 4583 \text{ psi} \quad \#\text{Cycles} = > 10^9 \text{ cycles}}$

$R = \dfrac{166.67}{13333} = 0.0125$

@ $\approx \dfrac{1 \text{ cyc}}{2 \text{ sec}}$, $\dfrac{\# \text{ cyc}}{\text{year}} = 15.7$ million cycle/yr.

LASTS 63 years!!!

$\dfrac{K_T \sigma_A}{S'_N} + \dfrac{\sigma_m}{S_u} = \dfrac{1}{N} \Rightarrow \dfrac{(1.0)(4583.33)}{(11502)} + \dfrac{(6750)}{45000} = 0.722$

$\dfrac{1}{.722} = \boxed{1.38 = N \text{ (Safety Factor)}}$

$\therefore$ Using 2.0 is safe!

ANALYSIS 20: Endurance strength, fatigue analysis, and recommended safety factor for wheel spokes.

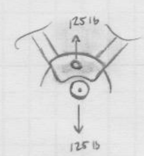
METU35   Joe Fischer   A-21

GIVEN: 1 bolts support 1 wheel section, 125 lb load on axle, 1/4"-20 bolt

FIND: Shear Stress

SOLN:

FBD



$\Sigma F_y = 0 = -125 + 2(F_B)$

$F_B = 62.5$ lb

$A = \frac{\pi}{4}(D^2) = \frac{\pi}{4}(.25)^2 = 0.04909 \text{ in}^2$

$\tau = \frac{F}{A} = \frac{62.5 \text{ lb}}{0.04909 \text{ in}^2} = \boxed{1273.24 \text{ psi}}$

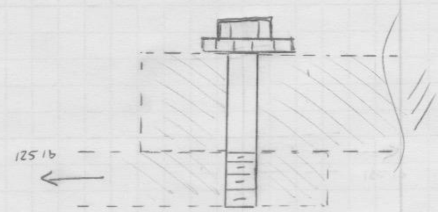
Clamp loads:

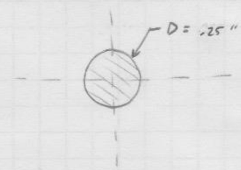
1/4"-20 → Grade 2 → 723 lb, 55 ksi

Safe Shear Strength → 7520 psi

200 lb @ thread root

370 lb @ Bolt





ANALYSIS 21: Shear stress analysis of hub bolts.

11-21-14 | MET 495 | Joe Fischer | 4-22

STRESS CONCENTRATION - SPOKE BASE

GIVEN: 125 lb load, 0.257" hole, A6061-T6

FIND: Stress Concentration, Design Factor

SOL'N:

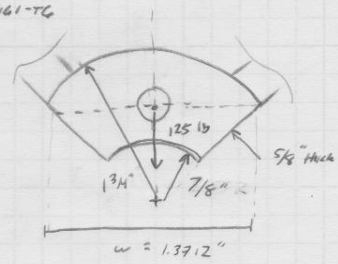


Fig. 3-29 : $\frac{d}{w} = \frac{0.257}{1.3712} = 0.1874$

$@ \frac{d}{w} = 0.1874 \quad , \quad K_T = 5.2$

$\sigma_{max} = \frac{125 \text{ lb}}{(1.3712 - 0.257)(5/8)} (5.2) = 933.4 \text{ psi}$

STATIC : $\boxed{933.4 \text{ psi} < \underset{\text{ADJUSTED YIELD STRENGTH}}{20{,}000 \text{ psi}} \quad \therefore \text{ SAFE } \checkmark}$

GOODMAN :

$\sigma_{max} = 933.4$ psi | $S_u = 45{,}000$ psi

$\sigma_{min} = 0$ psi | $S_y = 40{,}000$ psi

$\sigma_m = 466.7$ psi | $S_n = 20{,}000$ psi

$\sigma_a = 466.7$ psi

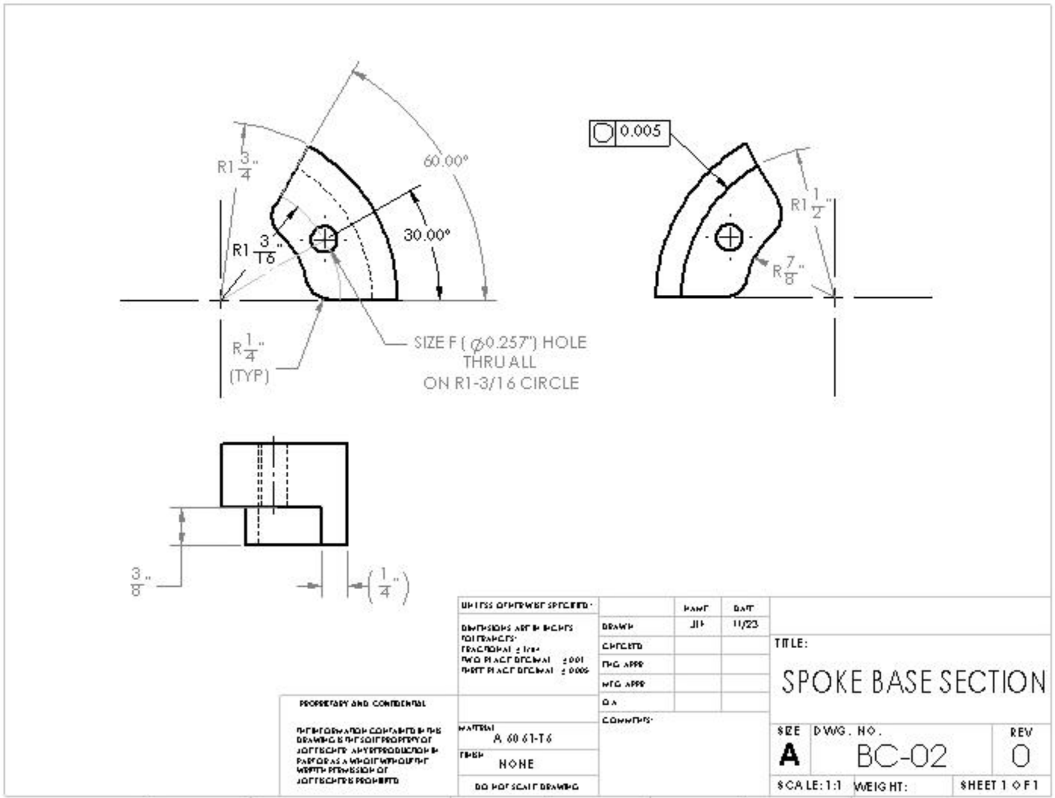
$S_n' = (20000)\underset{\text{wrought}}{(1.0)}\underset{\text{axial}}{(0.8)}\underset{.99\text{ reliable}}{(0.81)}(1) = 9201.6 \text{ psi}$

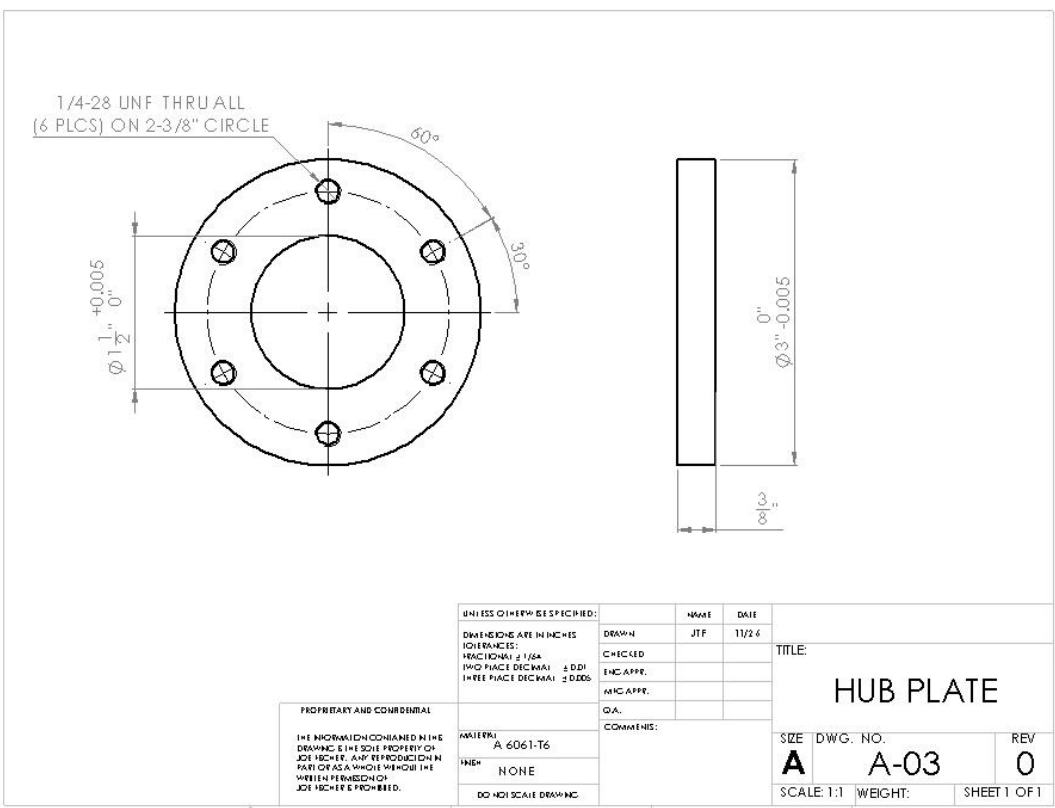
$N = \frac{1}{\frac{(5.2)(466.7)}{9201.6} + \frac{466.7}{20000}} = \boxed{3.45}$

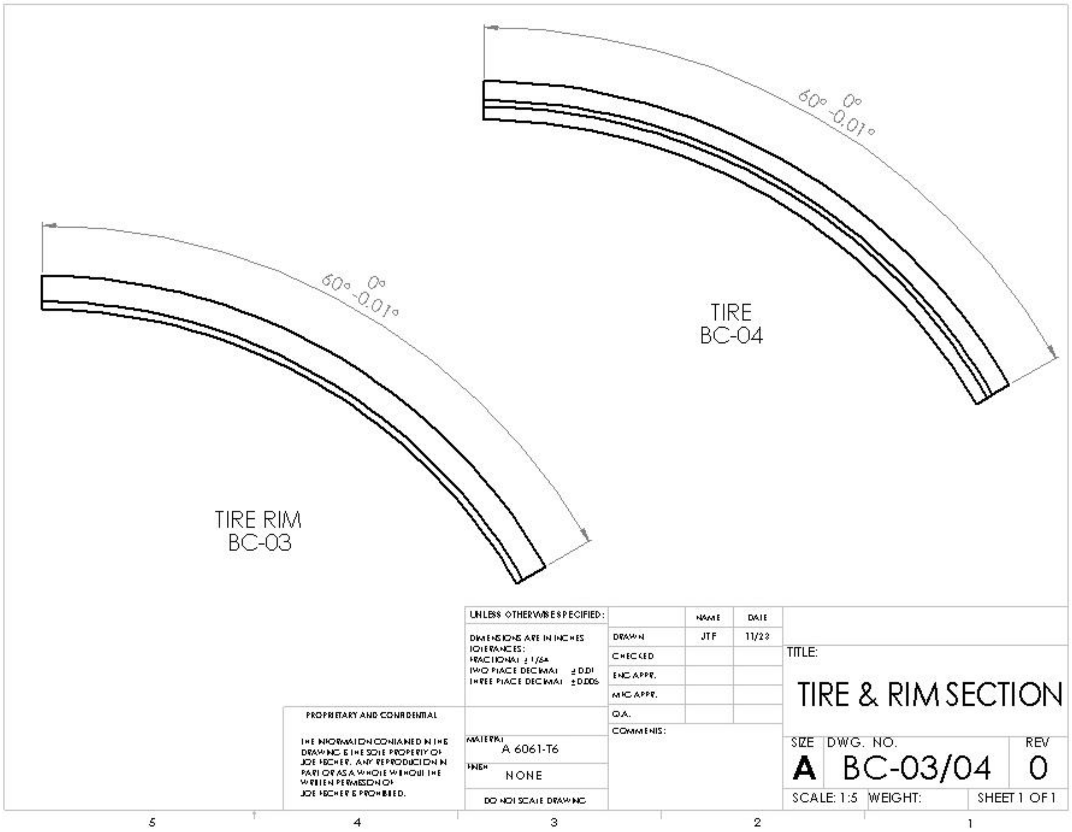
Fig. 5-7 : $@ \ \sigma_a = 466.7$ psi $\rightarrow$ # cycles = $\boxed{\text{off chart } (> 10^7 \text{ cycles})}$

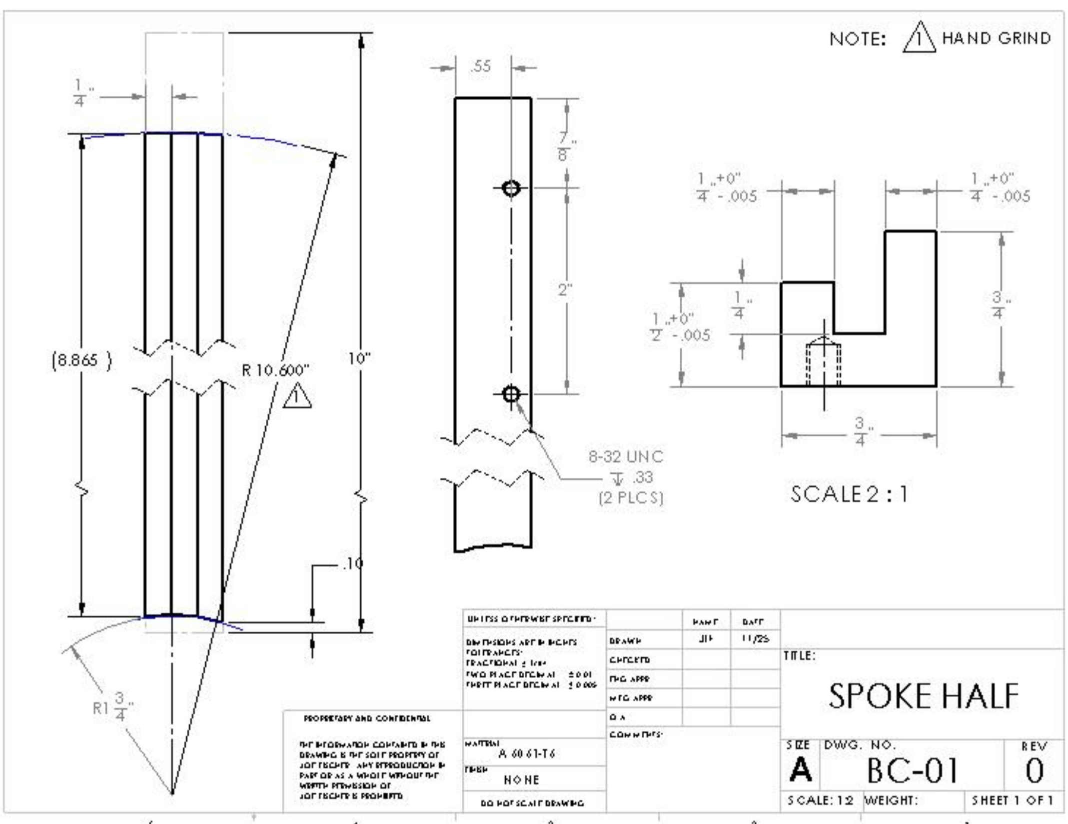
ANALYSIS 22: Stress concentration calculations for spoke base section.

APPENDIX B – Sketches, Assembly drawings, Sub-assembly drawings, Part drawings






60° 0°
-0.01°
60° 0°
-0.01°
TIRE
BC-04
TIRE RIM
BC-03
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/64
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
NAME
DATE
DRAWN
JTF
11/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF JOE FISCHER. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF JOE FISCHER IS PROHIBITED.
MATERIAL
A 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
TITLE:
TIRE & RIM SECTION
SIZE
DWG. NO.
REV
A
BC-03/04
0
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


NOTE: 1 HAND GRIND
1/4"
.55
7/8"
2"
1/4" +0" -.005
1/4" +0" -.005
1/4"
3/4"
1/2" +0" -.005
3/4"
(8.865)
R 10.600"
1
10"
8-32 UNC
↧ .33
(2 PLCS)
SCALE 2 : 1
.10
R1 3/4"
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/64
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
NAME
DATE
DRAWN
JTF
11/25
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
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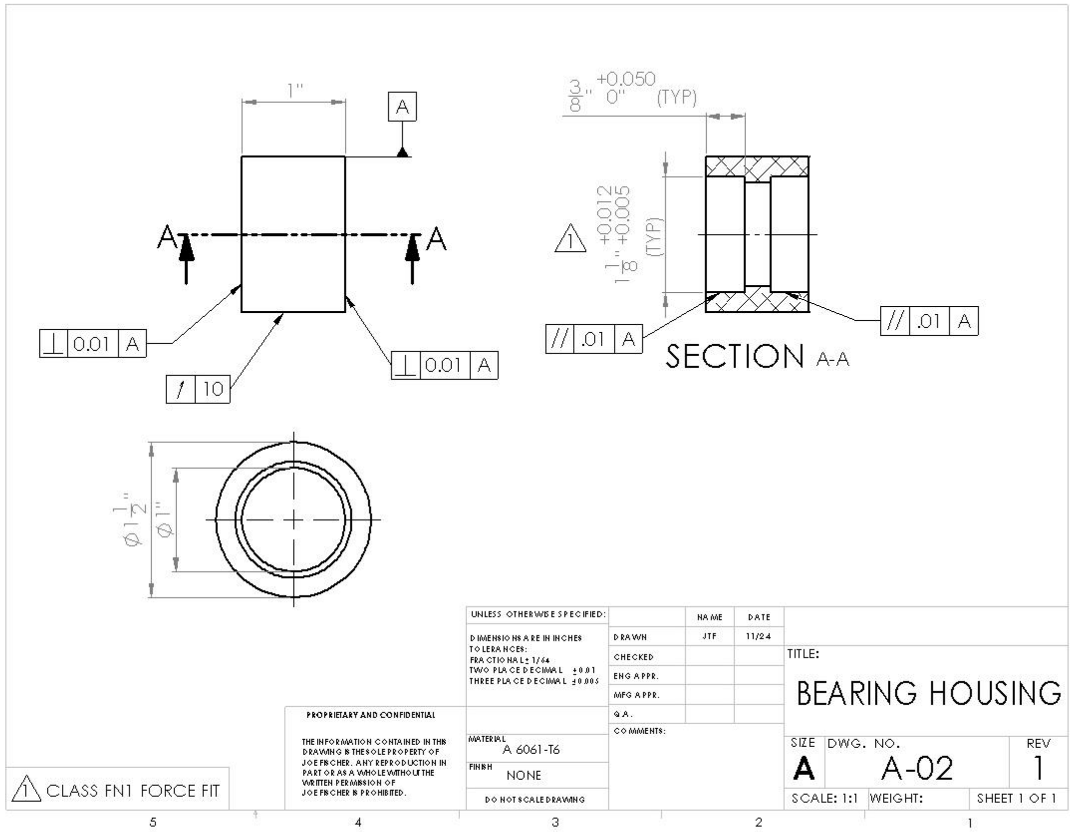
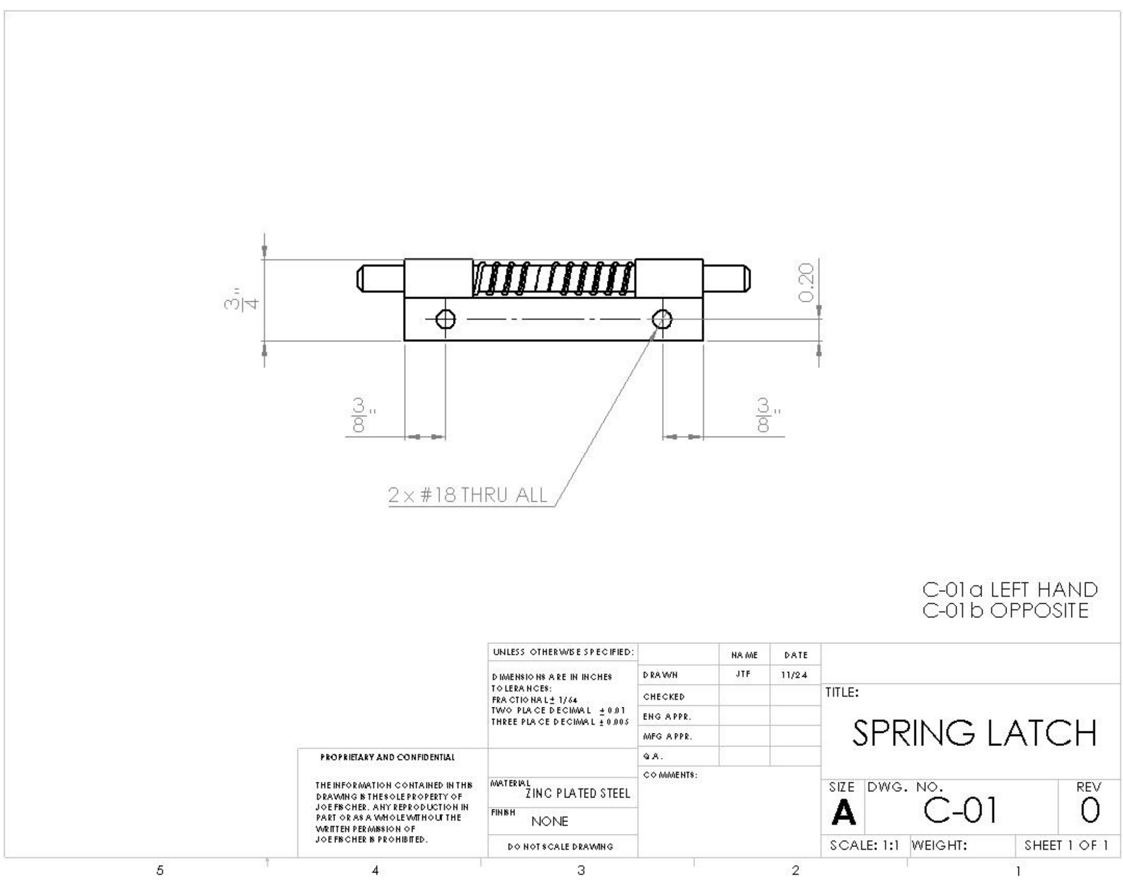
MATERIAL
A 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
TITLE:
SPOKE HALF
SIZE
DWG. NO.
REV
A
BC-01
0
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


BEARING HOUSING
A-02
CLASS FN1 FORCE FIT
SECTION A-A
MATERIAL A 6061-T6
FINISH NONE
DRAWN JTF 11/24
SIZE A DWG. NO. A-02 REV 1
SCALE: 1:1 WEIGHT: SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF JOE FISCHER. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF JOE FISCHER IS PROHIBITED.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/64
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
DO NOT SCALE DRAWING


2 x #18 THRU ALL
C-01a LEFT HAND
C-01b OPPOSITE
SPRING LATCH
MATERIAL ZINC PLATED STEEL
FINISH NONE
DRAWN JTF 11/24
SIZE A DWG. NO. C-01 REV 0
SCALE: 1:1 WEIGHT: SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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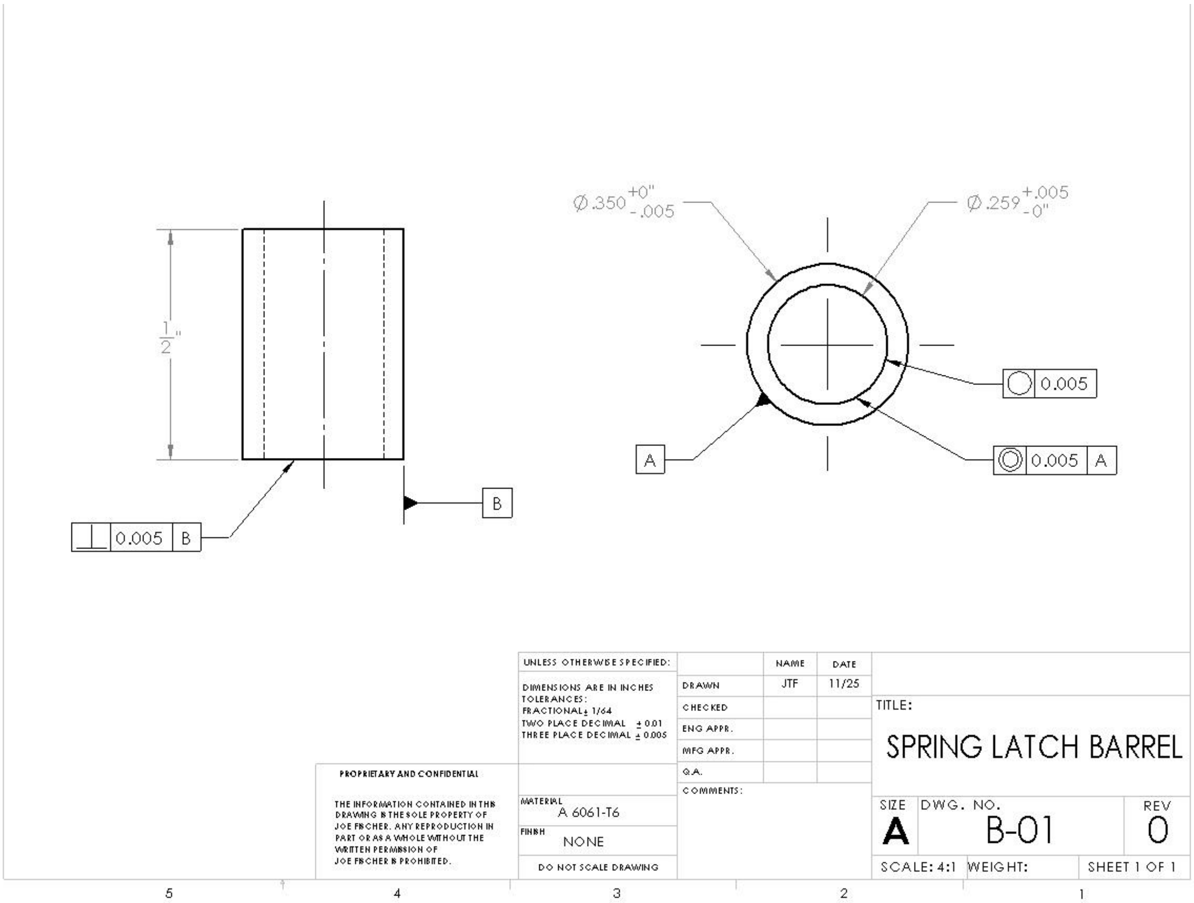
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/64
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
DO NOT SCALE DRAWING



Ø.350 +0" -.005
Ø.259 +.005 -0"
1/2"
0.005
0.005 A
A
B
0.005 B
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL± 1/64
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
NAME
DATE
DRAWN
JTF
11/25
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SPRING LATCH BARREL
PROPRIETARY AND CONFIDENTIAL
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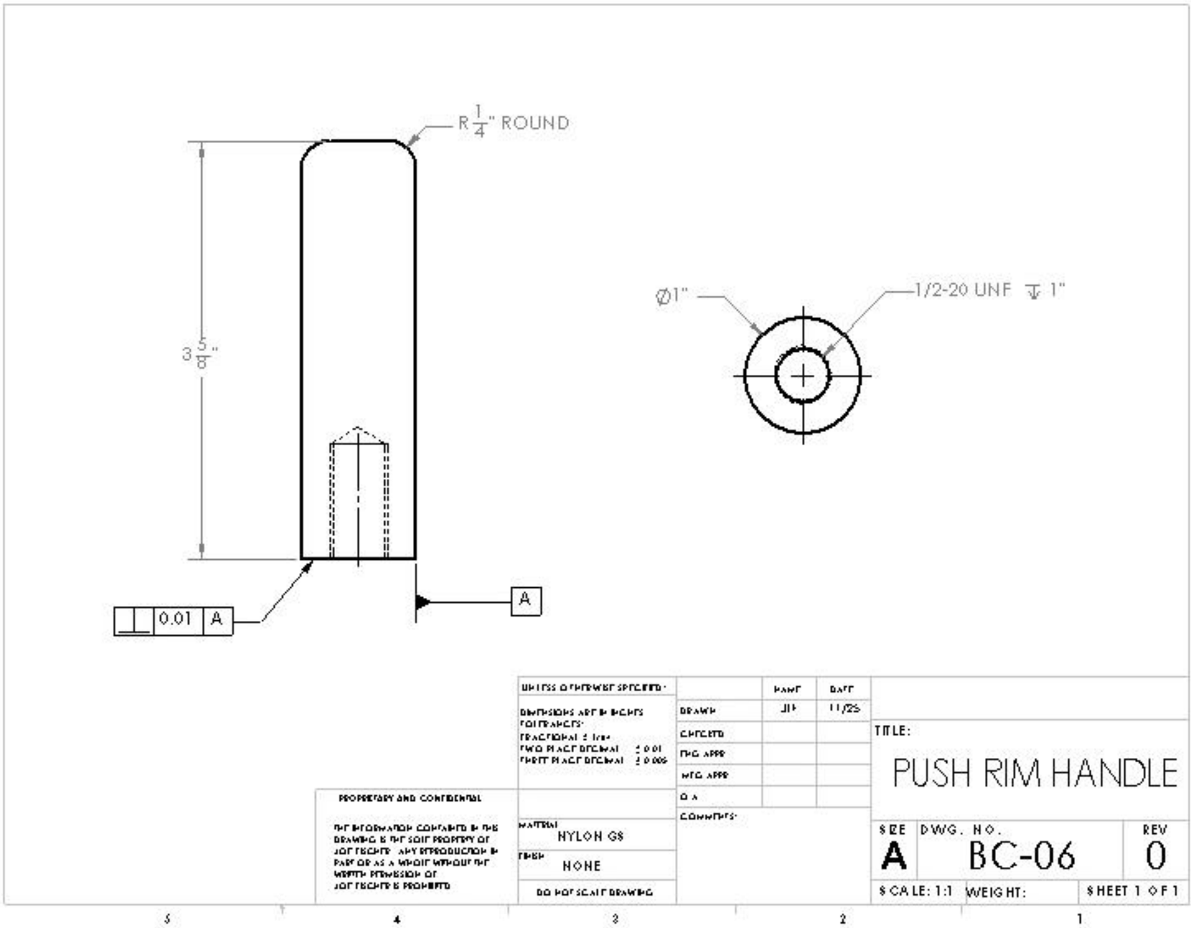
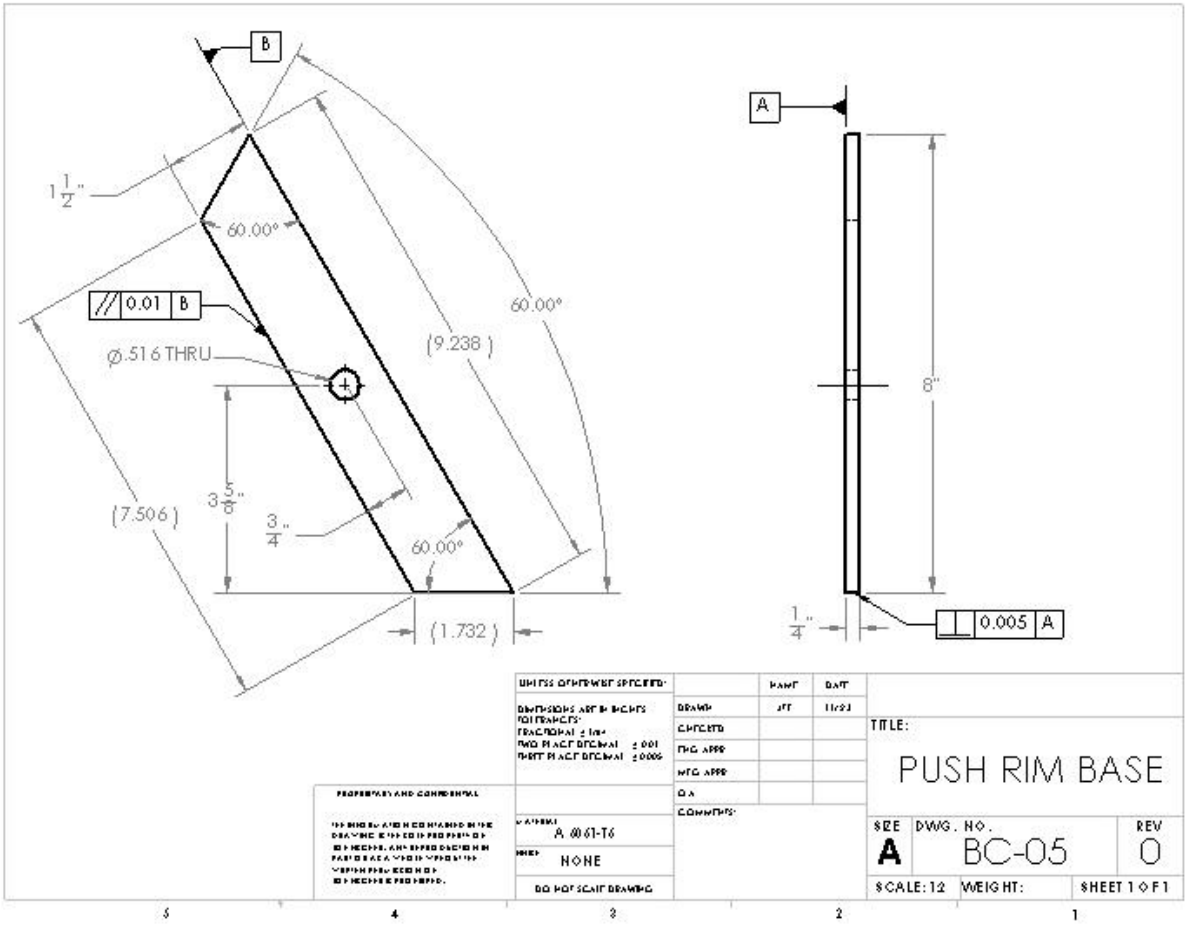
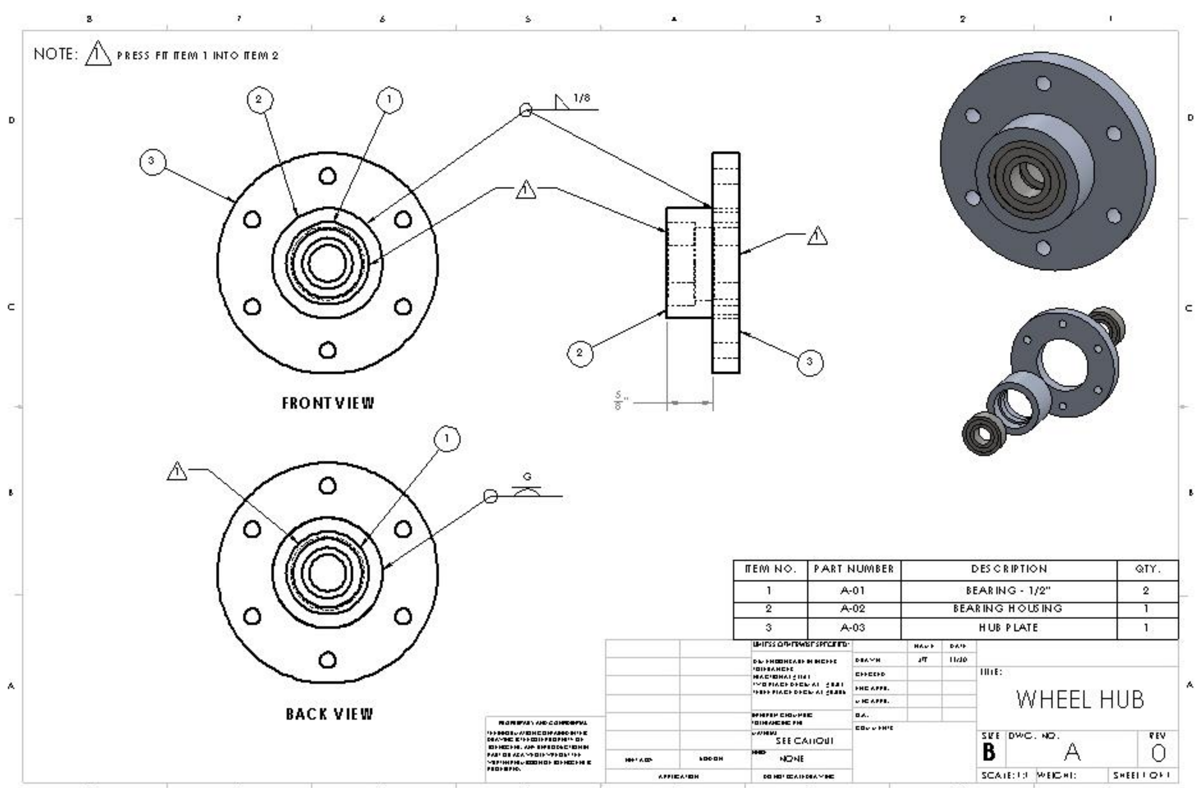
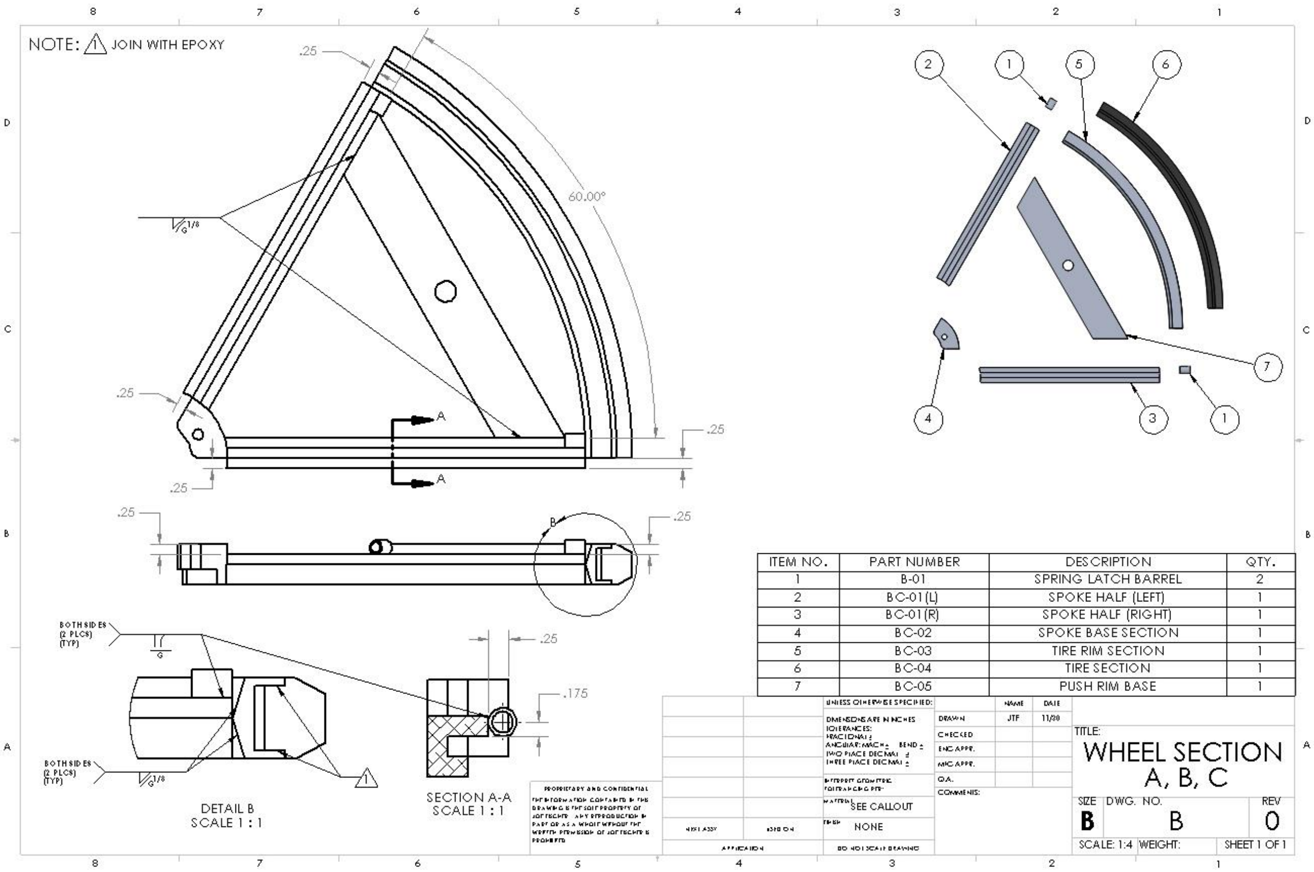
MATERIAL
A 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
SIZE
A
DWG. NO.
B-01
REV
0
SCALE: 4:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



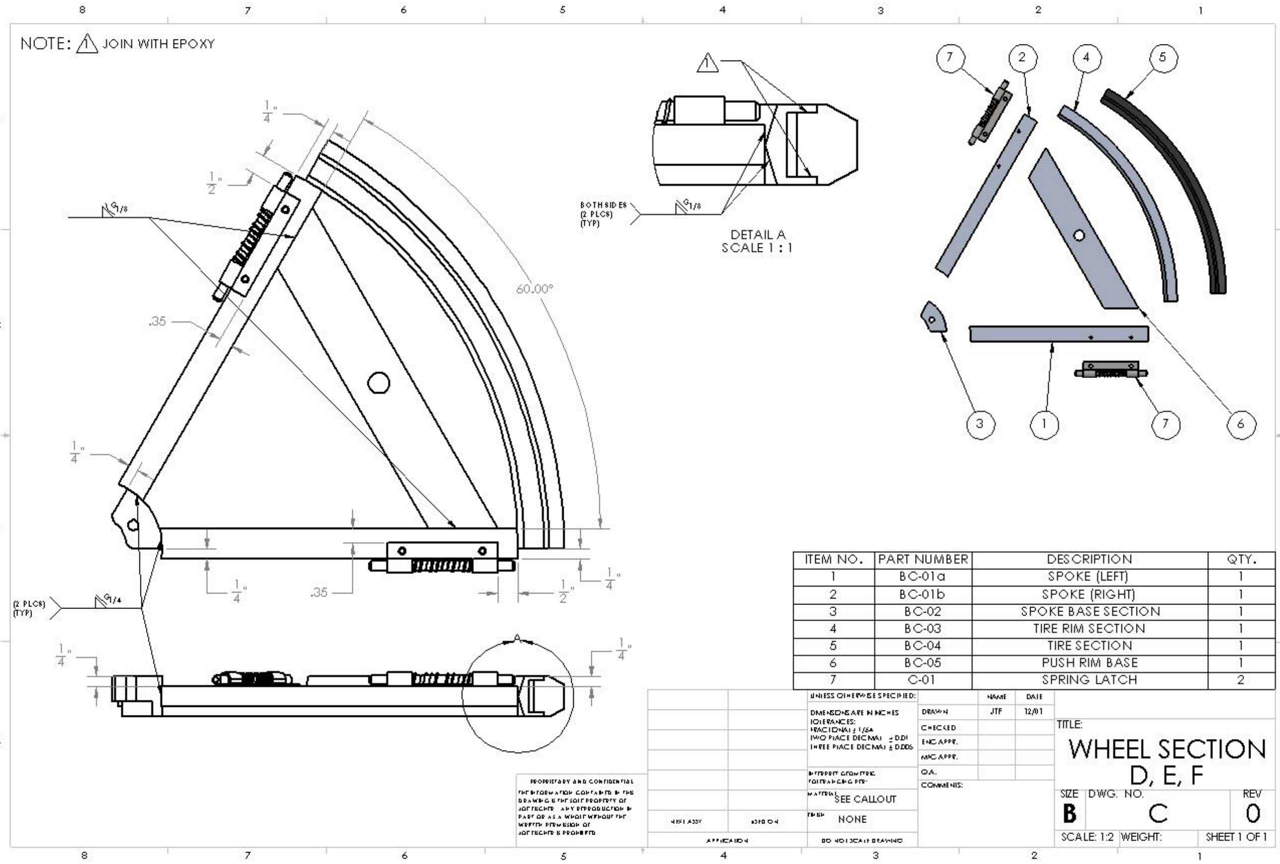
R 1/4" ROUND
3 5/8"
Ø1"
1/2-20 UNF ↧ 1"
0.01 A
A
NAME
DATE
DRAWN
TITLE:
PUSH RIM HANDLE
SIZE
DWG. NO.
REV
A
BC-06
0
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NONE


B
A
1 1/2"
60.00°
// 0.01 B
Ø.516 THRU
(9.238)
60.00°
8"
(7.506)
3 5/8"
3/4"
60.00°
(1.732)
1/4"
⊥ 0.005 A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/64
TWO PLACE DECIMAL ±.001
THREE PLACE DECIMAL ±.0005
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
A 6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
TITLE:
PUSH RIM BASE
SIZE
A
DWG. NO.
BC-05
REV
0
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

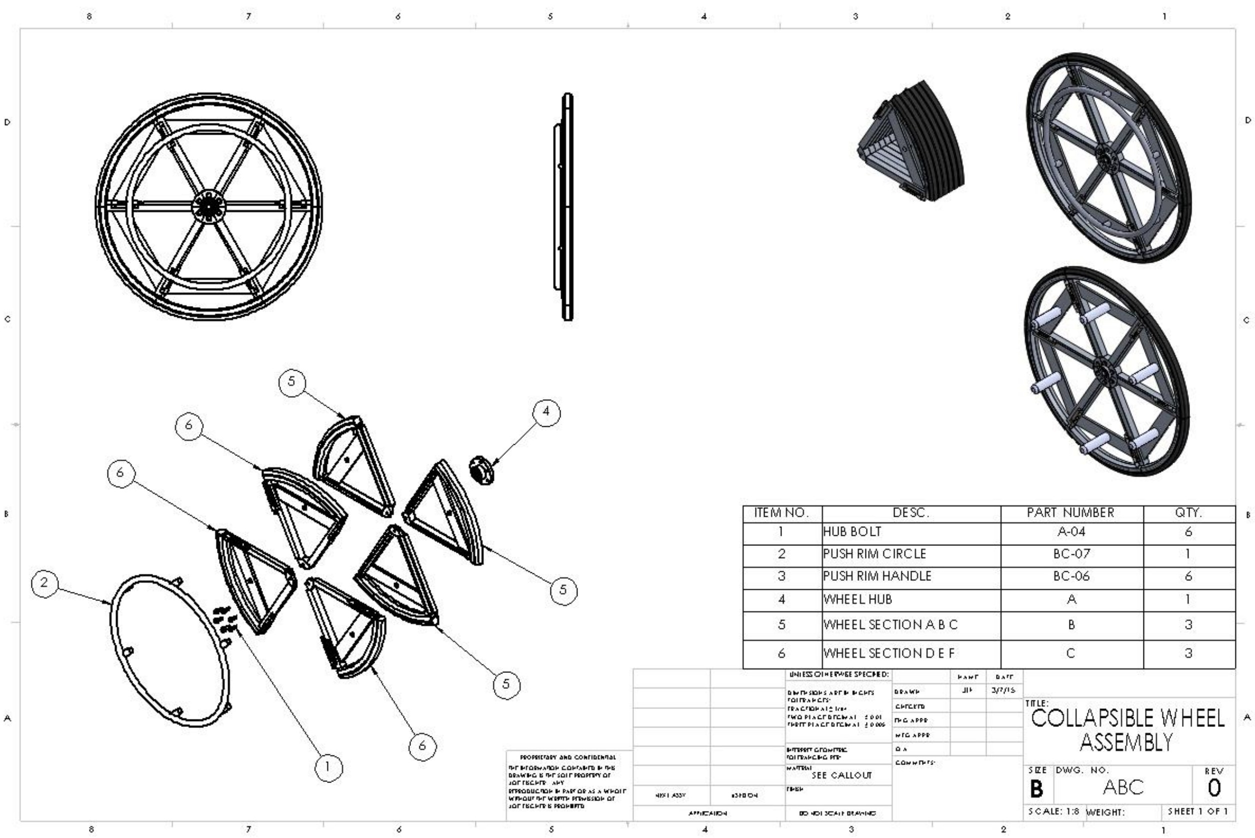

NOTE: PRESS FIT ITEM 1 INTO ITEM 2
1/8
5/8"
FRONT VIEW
BACK VIEW
G
ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | A-01 | BEARING - 1/2" | 2
2 | A-02 | BEARING HOUSING | 1
3 | A-03 | HUB PLATE | 1
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
MATERIAL
SEE CAD FILE
FINISH
NONE
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
TITLE:
WHEEL HUB
SIZE
B
DWG. NO.
A
REV
0
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	B-01	SPRING LATCH BARREL	2
2	BC-01(L)	SPOKE HALF (LEFT)	1
3	BC-01(R)	SPOKE HALF (RIGHT)	1
4	BC-02	SPOKE BASE SECTION	1
5	BC-03	TIRE RIM SECTION	1
6	BC-04	TIRE SECTION	1
7	BC-05	PUSH RIM BASE	1

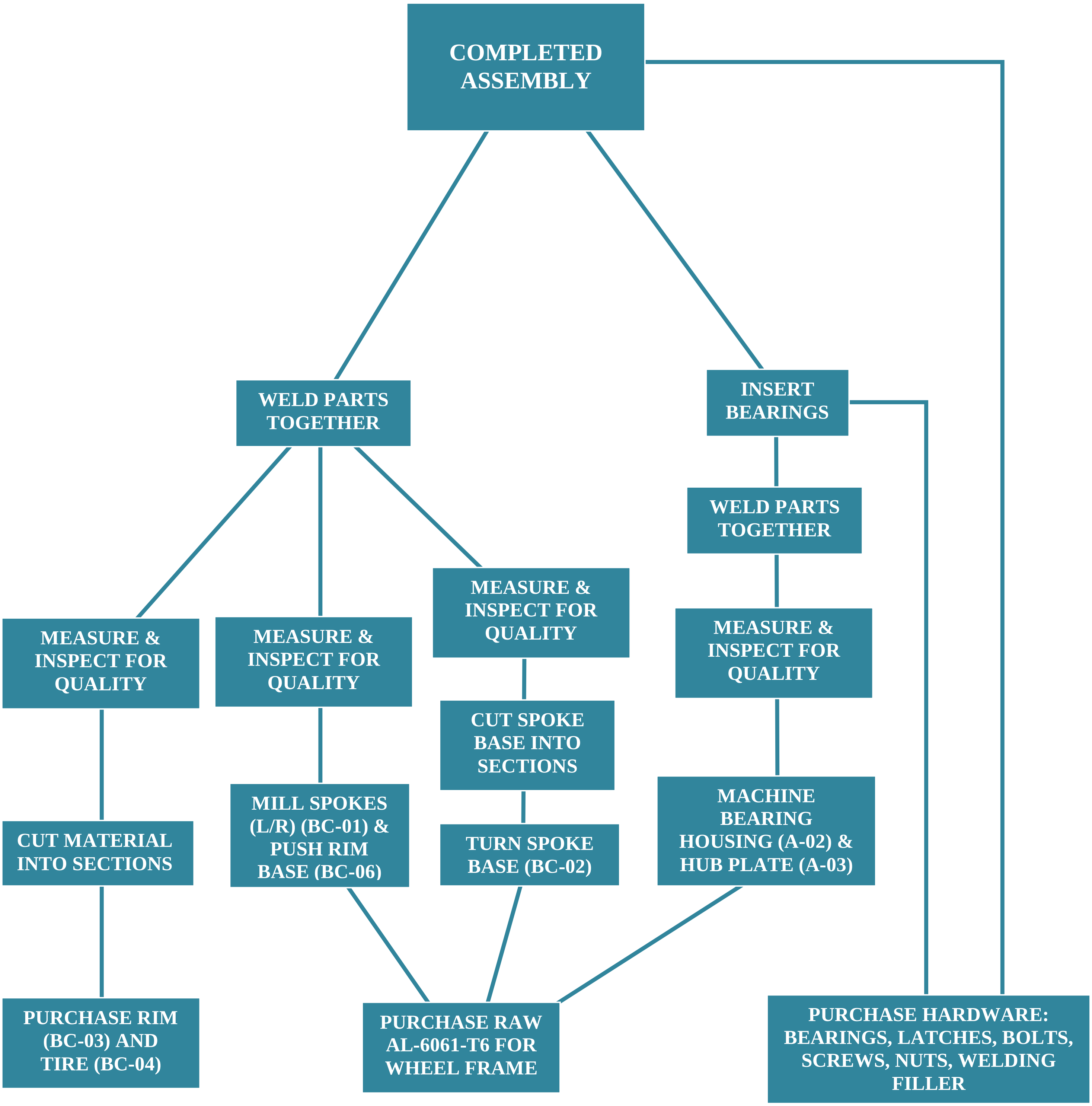


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	BC-01a	SPOKE (LEFT)	1
2	BC-01b	SPOKE (RIGHT)	1
3	BC-02	SPOKE BASE SECTION	1
4	BC-03	TIRE RIM SECTION	1
5	BC-04	TIRE SECTION	1
6	BC-05	PUSH RIM BASE	1
7	C-01	SPRING LATCH	2



ITEM NO.	DESC.	PART NUMBER	QTY.
1	HUB BOLT	A-04	6
2	PUSH RIM CIRCLE	BC-07	1
3	PUSH RIM HANDLE	BC-06	6
4	WHEEL HUB	A	1
5	WHEEL SECTION A B C	B	3
6	WHEEL SECTION D E F	C	3

APPENDIX C – Drawing Tree



APPENDIX D – Parts List

COLLAPSIBLE WHEEL PARTS LIST		
ITEM NO.	**DESCRIPTION**	**QUANTITY**
A-01.	Bearing – 1/2	1
A-02.	Bearing Housing	1
A-03.	Hub Plate	1
A-04.	Hex Flange Bolt 1/4 – 28 x .75	12
B-01.	Spring Latch Barrel	6
C-01a.	Spring Latch (L)	3
C-01b.	Spring Latch (R)	3
BC-01a.	Spoke Half (L)	6
BC-01b.	Spoke Half (R)	6
BC-02.	Spoke Base Section	6
BC-03.	Tire Rim Section	6
BC-04.	Tire Section	6
BC-05.	Push Rim Base	6
BC-06.	Push Rim Handle	6
BC-07.	Push Rim Circle	1
BC-08.	Threaded Stud 1/2 – 20 x 3/4	6

APPENDIX E – Budget

COLLAPSIBLE WHEEL PARTS AND COST LIST							
Item No.	**Description**	**Material**	**Cost**	**Quantity**	**Purchase Location**	**Total Cost**	**Actual Cost**
11126955	Hex Flange Bolt 1/4-20x1	Steel	$0.22	12	Fastenal	$2.64	$2.64
N/A	Ball Bearing – 1/2 ID x 3/8W	Steel	$0.00	2	N/A	$0.00	$0.00
A-SB-0110	Aluminum Square Bar – 1 x 60	Aluminum 6061-T6	$24.17	2	OnlineMetals	$48.34	$48.34
A-RT-0102	Aluminum Tube – 1 ID	Aluminum 6061-T6	$2.78	1	OnlineMetals	$2.78	$2.78
A-R-0302	Aluminum Round – 3.5 OD	Aluminum 6061-T6	$5.34	1	OnlineMetals	$5.34	$5.34
A-RB-010025	Aluminum Rect. Bar – 1.5 x .25 x 60	Aluminum 6061-T6	$9.06	1	OnlineMetals	$9.06	$9.06
A-RT-0010	Aluminum Tube - .259 ID x 10	Aluminum 6061-T6	$3.05	1	OnlineMetals	$3.05	$3.05
267-201-0982	Aluminum Rim - 26 x 1	Aluminum 6061-T6	$35.00	1	BikeWagon	$35.00	$35.00
N/A	Rubber Solid Tire – 1 x 3/4	Urethane Rubber	$0.00	1	N/A	$0.00	$0.00
HG-9252	Spring Latch Hinge (Left)	Steel	$3.28	3	Essentra	$9.84	$9.84
HG-9251	Spring Latch Hinge (Right)	Steel	$3.28	3	Essentra	$9.84	$9.84
47066	Threaded Stud – 1/2-20 x 36	Steel	$13.07	1	Fastenal	$13.07	$13.07
N-R-0124	Nylon Round – 1 x 24	Nylon GS	$18.59	1	OnlineMetals	$18.59	$18.59
1136260	Hex Jam Nut – 1/2-20	Steel	$0.29	6	Fastenal	$1.74	$1.74
N/A	Circle Push Rim	Nylon 6/6	$0.00	1	N/A	$0.00	$0.00
	Estimated Grand Total:		$162.07	Actual Grand Total:		$159.29	$159.29

APPENDIX F – Schedule

PROJECT TITLE: COLLAPSIBLE WHEEL

Principal Investigator: Joe Fischer

TASK: ID	**Description**	**Duration Est. (hrs)**	**Actual (hrs)**
1	**Proposal**		
1a	Outline	2	2
1b	Intro	5	5
1c	Methods	5	5
1d	Analysis	20	30
1e	Discussion	5	5
1f	Parts and Budget	10	20
1g	Drawings	5	10
1h	Schedule	5	5
1i	Summary & Appx	5	5
	subtotal:	62	87
2	**Analyses**		
2a	Research	10	10
2b	Static Forces	2	2
2c	Stress Analysis	5	5
2d	Deflect.	5	5
2e	Alt. Mtrl	5	10
2f	Alt. Design	10	15
	subtotal:	37	47
3	**Documentation**		
3a	Spoke drawing	2	3
3b	Hub drawing	2	1
3c	Rim drawing	2	2.5
3d	Spoke attachment	2	3.2
3e	Purchase parts	2	2
3f	Part A/B subassembly	2	2.2
3g	Assembly drawing	4	4.5
	subtotal:	16	17.9
4	**Part Construction**		
7a	Buy AL stock	1	1.5
7b	Buy parts	5	7
7c	Make hub	5	3.5
7d	Make spokes	15	10.2
7e	Make spoke base	10	14
7f	Cut rim sections	2	2.7
7g	Fit hinges	4	2.5
7h	Hole locations	3	2
7i	Make push rim	5	5.5
	subtotal:	50	48.9
9	**Device Construct**		
9a	Welding hub	2	0.5
9b	Welding spokes	2	2
9c	Weld rim	2	2
9d	Mate tire	2	3.5
9e	Take Dev Pictures	1	0.5
9f	Update Website	3	5
	subtotal:	12	13.5
10	**Device Evaluation**		
10a	List Parameters	2	1
10b	Design test & scope	5	6.7
10c	Obtain resources	2	5
10d	Make test sheets	2	6.2
10e	Plan analyses	5	4.5
10f	Install wheel	2	2
10g	Test plan	4	6.7
10h	Perform evaluation	10	12
10i	Take testing pics	1	1
10h	Update website	3	4
	subtotal:	36	49.1
11	**495 Deliverables**		
11a	Get Report Guide	1	0.5
11b	Make Rep Outline	4	7.5
11c	Write Report	15	8
11d	Make Slide Outline	2	3
11e	Create Presentation	5	7.2
11f	Make CD Deliv. List	2	2
11e	Write 495 CD parts	2	2
11f	Update Website	10	11
11g	Project CD*	2	2
	subtotal:	43	43.2
	Total Est. Hours=	**256**	**306.6**

APPENDIX G – Expertise and Resources

MENTORS:

Dr. Craig Johnson
Mr. Charles Pringle
Mr. Roger Beardsley
Mr. Patrick Hansen

CONSULTANTS:

Mrs. Jenny Ford

FABRICATORS:

Joe Fischer
Mr. Matthew Burvee
Mr. Patrick Hansen

BUSINESSES/ASSOCIATIONS/ORGANIZATIONS:

Central Washington University
Better Living Retirement Homes

APPENDIX H – Evaluation sheet (Testing)

COLLAPSIBLE WHEEL ASSEMBLY / DISASSEMBLY TEST					
Name:					
Date:					
Trial Number:					
		Without Instructions		With Instructions	
Participant (#)	Age (years-old range)	Time (assemble) (seconds)	Time (disassemble) (second)	Time (assemble) (seconds)	Time (disassemble) (seconds)
1	15-20				
2					
3					
4					
5	21-30				
6					
7					
8					
9	31-40				
10					
11					
12					
13	41-50				
14					
15					
16					
17	51-60				
18					
19					
20					

WHEEL DEFLECTION UNDER VARIOUS LOADS				
Name:				
Date:				
Trial Number:				
Load (lb.)	Trial (#)	Deflection @ loc. 1 (in.)	Deflection @ loc. 2 (in.)	Deflection @ loc. 3 (in.)
250	1			
	2			
	3			
	4			
	5			
300	1			
	2			
	3			
	4			
	5			
350	1			
	2			
	3			
	4			
	5			
400	1			
	2			
	3			
	4			
	5			
450	1			
	2			
	3			
	4			
	5			

TERRAIN, STABILITY, AND COMFORT TEST									
Name:									
Date:									
Trial Number:									
Trial (#)	Weight of Participant (lb.)	Flat Surface Rating (1-10)	Uphill Slope Rating (1-10)	Gravel Rating (1-10)	Ledge Rating (1-10)	Grass / Foliage Rating (1-10)	Sand / Mud Rating (1-10)	Total Score	Comments
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									

PHYSICAL PROPERTIES EVALUATION				
Name:				
Date:				
Trial Number:				
Dimension	**Benchmark**	**Predicted**	**Actual**	**Notes**
Uncollapsed Height	24.0 in.	24.0 in.		
Uncollapsed Width	24.0 in.	24.0 in.		
Uncollapsed Depth	4.0 in.	1.0 in.		
Collapsed Height	12.5 in.	10.75 in.		
Collapsed Width	32.0 in.	11.25 in.		
Collapsed Depth	4.0 in.	6.0 in.		
Frontal Area	452.4 in.^{2}	75.4 in.^{2}		
Weight	7.5 lb.	10.9 lb.		

APPENDIX I – Testing Report

Collapsible Wheelchair Wheel
Testing Report

By:
Joe Fischer

Central Washington University
MET 495
Spring 2015

INTRODUCTION

This project will be tested in Quarter 3 starting March 2015. The first method of testing will include strain gauging specific areas of interest including the spokes halves, the tire rim, and the hub under the maximum capacity load. These measured values will be compared to the analysis calculations and finite element analysis. It is important these critical locations do not fail or deflect past the design requirement. Since this project is intended for the elderly, handicapped, and people in general, it is crucial the wheel does not fail.

APPROACH

Since the purpose of this project is to produce a wheel that is as compact as possible, it is important to test the size and weight of the wheel after constructed, both collapsed and open. The requirement states that the wheel must collapse to less than 50% of its original area in order to compete with its competition. The requirements also state that the wheel must weigh less than 10 pounds to be considered a success. This will be done by traditional measuring methods and compared to the predicted dimensions and weight along with the benchmark and other portable wheelchair wheels on the market.

The collapsible wheel will be attached to the wheelchair axle and loaded to 250 lb. Strain gauge measurements will be taken at critical locations. This will be repeated several times. The strain will also be measured in linear motion as well as over rigid terrain and over ledges. It is also important to test other shock loads, as elderly and injured wheelchair users are often “popped” into their wheelchairs, causing extra stresses in the wheels. [8] This will be repeated with increased loads up to 500 lb. to verify the calculations with a safety factor of 2.0.

The Tinius Olsen in the Hogue Technology Building will be used to test individual spoke columns to determine maximum tensile stress and deflection. For this test, additional spokes will be manufactured. The results will be compared to the analysis and FEA results.

According to the requirements, the wheel must easily fold and unfold within 60 seconds and contain a set of instructions for proper use. Many time trials of folding and unfolding the wheel will be conducted to gauge whether or not this design meets the benchmark for ease of use and efficiency. This will be performed by different people of different ages multiple times after carefully reading the provided instructions.

PROCEDURE

TEST 1: Assembly Efficiency Test
Appendix H - pg. 1

16. Start with wheel in uncollapsed form, attached to the wheelchair axle.
17. Have stop watch and all accompanied tools ready.
18. Have participant disassemble the wheel when told to “start”.
19. Start timing.
20. Stop timing when wheel is fully in its collapsed state.
21. Record time.
22. Have participant reassemble the wheel and attach it to wheelchair axle when told to “start”.
23. Start timing.

24. Stop timing when wheel is fully assembled and attached to wheelchair.
25. Record time.
26. Have participant read the provided User Manual for instructions on how to properly assemble and disassemble the wheel.
27. Repeat Steps 1-10 and record the new time.
28. Repeat Steps 1-12 with other participants of various ages.
29. Compare assembly time with benchmark and other collapsible wheels.
30. Visually demonstrate the effectiveness of the provided instructions in User Manual.

TEST 2: Deflection Under Load
Appendix H – pg. 2

7. Attach wheel in uncollapsed form to wheelchair axle.
8. Attach strain gauges to the critical locations:
    a. Rim, midpoint between spokes.
    b. Spoke, wall and face.
9. For 4 – 7 inches above the seat, have the 250-pound human specimen sit into wheelchair in a “plopping” motion.
10. Record strain values.
11. Repeat 10 times.
12. Repeat steps 3 – 5 with 300-pound human specimen.

TEST 3: Terrain Test
Appendix H – pg. 3

10. Attach Collapsible Wheel to wheelchair.
11. Use human specimen of approximately 250 pounds.
12. With the specimen in the wheelchair, have one person push the wheelchair 10 yards on a smooth, flat surface.
13. Have the second person observe and interrogate the Collapsible Wheel as it traverses the surface. The observer will rate the wheels performance on a scale of 1-10 based on these parameters:
    a. Stability
    b. Wobbling
    c. Concentricity
    d. Solidness of Assembly
    e. Deflection / Bending
    f. Fluidity while Moving
    g. Ride comfort
14. At the end of 10 yards, the specimen will turn around and propel himself/herself using the push rims for the returning 10 yards.
15. The second person will observe and interrogate again and take special note of how the user interacts with the push rim.
16. Repeat steps 3-6 with various users of different weight and age.
17. Repeat steps 2-7 with various terrain, such as slopes, gravel, mud, grass, rain, etc.
18. Compare the rating from each test to determine the strengths and weaknesses and whether weight is affecting the performance.

TEST 4: Single Spoke Strength
Appendix H – pg. 4

10. Load one spoke into Tinius Olsen.
11. Zero out dial indicator.
12. Zero out deflection gauge.
13. Load in increments of 50 lb. up to 450 lb.
14. Record the readings at each load increment.
15. Unload device.
16. Repeat steps ‘x’ times for consistency.
17. Plot data using Excel.
18. Compare values to analysis calculation and FEA predictions.

DELIVERABLES

PHYSICAL PROPERTIES EVALUATION

Name: [illegible]

Date: 9-10-15

Trial Number: #1

Dimension	**Benchmark**	**Predicted**	**Actual**	**Notes**
Uncollapsed Height	24.0 in.	24.0 in.	23.5 in.	Different Tire – Easily Adaptable
Uncollapsed Width	24.0 in.	24.0 in.	23.5 in.	
Uncollapsed Depth	4.0 in.	1.0 in.	1.1 in.	Rubber Tire Overhang
Collapsed Height	12.5 in.	10.75 in.	10.375 in.	
Collapsed Width	32.0 in.	11.25 in.	11.250 in.	
Collapsed Depth	4.0 in.	6.0 in.	6.6 in.	
Frontal Area	452.4 in.^{2}	~~71.9 in.^{2}~~ 75.4 in^2	72.3 in^2	
Weight	7.5 lb.	10.9 lb.	12.3 lb	Lighter Rubber Tires?

COLLAPSIBLE WHEEL ASSEMBLY / DISASSEMBLY TEST

Name: Joe Fischer

Date: 4-11-15 - 4-26-15

Trial Number: #1

Participant (#)	Age (years-old range)	Without Instructions: Time (assemble) (seconds)	Without Instructions: Time (disassemble) (second)	With Instructions: Time (assemble) (seconds)	With Instructions: Time (disassemble) (seconds)
1	15-20	5:32.5	3:08.6	5:27.0	2:23.1
2		7:40.3	4:53.0	7:10.7	4:01.8
3		10:03.8	3:58.7	4:40.3	2:41.6
4		8:25.3	4:15.0	6:03.8	3:11.1
5	21-30	8:31.5	5:20.4	4:10.7	5:06.8
6		8:56.1	3:08.5	5:58.0	2.49.7
7		5:21.1	4:13.2	5:09.6	3.13.8
8		6:18.3	2:41.7	3:14.1	2:18.1
9	31-40	5:41.6	4:06.7	5:04.0	2:31.5
10		8:21.2	5:27.2	6:13.7	2:45.0
11		4:33.3	4:16.6	4:37.9	3:17.3
12		5:01.5	3:18.9	4:29:2	2:50.9
13	41-50	6:38.2	3:42.0	5:08.1	2:25.0
14		6:21.9	2:33.3	4:44.2	2:12.7
15		7:48.0	4:19.2	6:01.7	3:50.4
16		10:18.3	6:02.8	6:47.5	4:34.7
17	51-60	6:18.8	3:21.1	4:04.8	2:50.5
18		5:56.1	3:51.6	4:52.2	3:27.6
19		5:42.2	2:50.8	3:38.7	2:52.2
20		8:21.5	4:52.4	5:05.4	4:11.6

WHEEL DEFLECTION UNDER VARIOUS LOADS

Name: Joe Fischer

Date: 5-2-15

Trial Number: #1

Load (lb.)	Trial (#)	(TIRE RIM) Deflection @ loc. 1 (in.)	(SPOKE) Deflection @ loc. 2 (in.)	(HUB) Deflection @ loc. 3 (in.)
250	1	0.0063	0.0070	0.000
	2	0.0059	0.0071	0.000
	3	0.0061	0.0072	0.000
	4	0.0058	0.0072	0.000
	5			
300	1	0.0082	0.0111	0.000
	2	0.0082	0.0102	0.000
	3	0.0090	0.0108	0.000
	4	0.0107	0.0110	0.000
	5			
350	1	0.0125	0.0212	0.000
	2	0.0137	0.0198	0.000
	3	0.0138	0.0208	0.000
	4	0.0129	0.0190	0.000
	5			
400	1	0.0177	0.0337	0.001
	2	0.0167	0.0322	0.001
	3	0.0176	0.0351	0.001
	4	0.0170	0.0300	0.001
	5			
450	1	0.0200	0.0598	0.001
	2	0.0208	0.0612	0.002
	3	0.0211	0.0611	0.002
	4	0.0211	0.0608	0.002
	5			

TERRAIN, STABILITY, AND COMFORT TEST

Name: Jez Fischer

Date: 5-6-15

Trial Number:

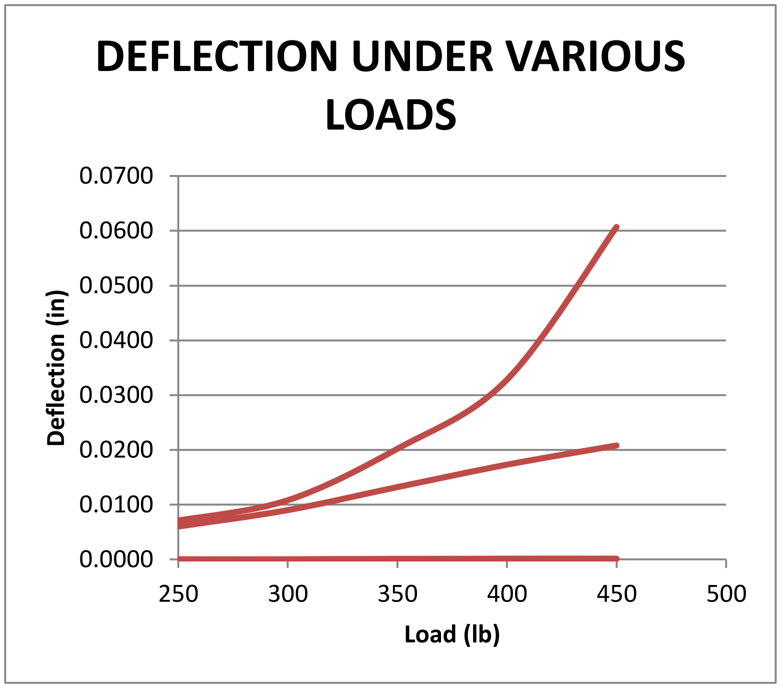
Trial (#)	Weight of Participant (lb.)	Flat Surface Rating (1-10)	Uphill Slope Rating (1-10)	Gravel Rating (1-10)	Ledge Rating (1-10)	GRASS/WEEDS Grass / Foliage Rating (1-10)	MUD/DIRT Sand / Mud Rating (1-10)	Total Score/ AVG.	Comments
1	210	9	9	7	7	9	5	46 / 7.7	Mud/Gravel between tire
2	155	9	9	6	7	9	5	45 / 7.5	
3	185	10	9	8	7	10	8	52 / 8.7	
4	255	9	9	6	8	8	8	48 / 8.0	Slight wobble - Ledge
5	135	10	10	6	8	8	5	47 / 7.8	
6	266	10	10	8	6	10	9	53 / 8.8	
7	250	10	9	9	6	9	4	47 / 7.8	
8	170	9	8	7	6	9	5	46 / 7.7	
9	190	10	10	7	8	9	5	49 / 8.2	
10	210	9	8	6	6	8	4	41 / 6.8	

RESULTS

COLLAPSIBLE WHEEL ASSEMBLY TEST				
participant	assemble 1	disassemble 1	assemble 2	disassemble 2
1	05:32.5	03:08.6	05:27.0	02:23.1
2	07:40.3	04:53.0	07:10.7	04:01.8
3	10:03.8	03:58.7	04:40.3	02:41.6
4	08:25.3	04:15.0	06:03.8	03:11.1
5	08:31.5	05:20.4	04:10.7	05:00.8
6	08:56.1	03:08.5	05:58.0	02:49.7
7	05:21.1	04:13.5	05:09.6	03:13.8
8	06:18.3	02:41.7	03:14.1	02:18.1
9	05:41.6	04:00.7	05:04.0	02:31.5
10	08:21.2	05:27.2	06:13.7	02:45.0
11	04:33.3	04:16.6	04:37.9	03:17.3
12	05:01.5	03:18.9	04:29.2	02:50.9
13	06:38.2	03:42.0	05:08.0	02:25.0
14	06:21.9	02:33.3	04:44.2	02:12.9
15	07:48.0	04:19.2	06:01.7	03:50.4
16	10:18.3	06:02.8	06:47.5	04:34.7
17	06:18.8	03:21.1	04:04.8	02:50.5
18	05:56.1	03:51.6	04:52.2	03:27.6
19	05:42.2	02:50.8	03:38.7	02:52.2
20	08:21.5	04:52.4	05:05.4	04:11.6
AVG	**without instruction**		**with instruction**	
	07:05.6	**04:00.8**	**05:08.1**	**03:10.5**
% IMPROV			**assembly**	**27.6%**
			disassembly	**20.9%**

The collapsibility test revealed that most people could not assemble the wheel within the 5-minute goal or disassemble it within the 3-minute goal. The average time for assembly was 7:05.6 and 4:00.8 for disassembly. The reason the assembly takes longer that expected is because of the welding alignment issues that occurred during the construction phase. This problem forced the wheel sections to have to be assembled in a particular order, ultimately adding time to the assembly process. Another area that can be improved is the hub screw. Replacing the hub fasteners with quick-release bolts would reduce the assembly and disassembly time by over a minute. What helped significantly is the instruction manual. After letting the user read the instructions for 5-10 minutes, the assembly time improved 27.6% and closer to the requirement goal of 5 minutes. This is also true for the disassembly time of 3:10.5 on average.

DEFLECTION UNDER VARIOUS LOADS TEST		
location	load	avg. deflection (4 trials)
	(lb)	(in)
RIM	250	0.0060
	300	0.0090
	350	0.0132
	400	0.0173
	450	0.0208
SPOKE (h)	250	0.0071
	300	0.0108
	350	0.0202
	400	0.0328
	450	0.0607
SPOKE (v)	250	0.0000
(buckling)	300	0.0000
	350	0.0001
	400	0.0001
	450	0.0001
HUB	250	0.0000
	300	0.0000
	350	0.0000
	400	0.0001
	450	0.0001



Test 2 was important for testing the maximum weight capacity and deflection requirements. According to the requirements, a pair of wheels should be able to support a 250-pound load and deflect no more than 0.050 inches in any location. The test at each weight load was performed 4 times and the deflection at each location was recorded. The average deflection of the 4 trials is shown in the table on the left. At only one instant the deflection exceed 0.050 inches. When loaded at 450 pounds, the horizontal spoke deflected 0.060 inches. Even though 450 pounds is far greater than the 250-pound requirement, according to the FEA and Safety factor of 2.0, the spoke should not have deflected more than 0.050 inches. However, this does make sense since this test used impact force to simulate how the wheels would actually be loaded in real-world scenarios whereas the FEA only calculated static loads.

TERRAIN, STABILITY, AND COMFORT TEST									
trial	weight	flat surface	uphill slope	gravel	ledge	grass/foliage	mud/dirt	total score	percent grade
1	210	9	9	7	7	9	5	46	76.7%
2	155	9	9	6	7	9	5	45	75.0%
3	185	10	9	8	7	10	8	52	86.7%
4	255	9	9	6	8	8	8	48	80.0%
5	135	10	10	6	8	8	5	47	78.3%
6	200	10	10	8	6	10	9	53	88.3%
7	250	10	9	9	6	9	4	47	78.3%
8	170	9	8	7	6	9	5	44	73.3%
9	190	10	10	7	8	9	5	49	81.7%
10	210	9	8	6	6	8	4	41	68.3%
Grading Criteria:									
2 = Superb. No problems. Performs perfectly.									
1 = Average. Doesn't perform perfectly but still within parameters.									
0 = Bad. Performs below average and below expectations.									
Grading Categories:									
1. Ride Comfort / Smoothness									
2. Stability / Rigidity									
3. Concentricity									
4. Deflection / Bending / Warping									
5. Ease of Use									

This test was important for ensuring the Collapsible Wheel performed to the standards of a traditional wheel. It is important that this new wheel does not cause any discomfort and is able to maintain functionality over various terrain just as well as a traditional wheel.

According to the traditional wheel test (top table), the average rating was 84.7%. The average rating for the Collapsible Wheel test (bottom table) was 78.7%. This difference was a result of the Collapsible wheel having some "wobble" due to its profile being thinner. There was also some concern on the gravel, grass, and dirt courses due the gaps between the tire sections getting clogged and causing discomfort and instability.

PHYSICAL PROPERTIES EVALUATION				
Name: Joe Fischer				
Date:				
Trial Number:				
Dimension	**Benchmark**	**Predicted**	**Actual**	**Notes**
Uncollapsed Height	24.0 in.	24.0 in.	23.5 in.	Different tire height than expected
Uncollapsed Width	24.0 in.	24.0 in.	23.5 in.	
Uncollapsed Depth	4.0 in.	1.0 in.	1.1 in.	Rubber tire overhang
Collapsed Height	12.5 in.	10.75 in.	10.375 in.	
Collapsed Width	32.0 in.	11.25 in.	11.250 in.	
Collapsed Depth	4.0 in.	6.0 in.	6.6 in.	
Frontal Area	452.4 in.^{2}	75.4 in.^{2}	72.3 in.^{2}	
Weight	7.5 lb.	10.9 lb.	10.3 lb.	Lighter rubber than SolidWorks model? Pushrim is a less dense metal than expected?

It was also important to measure the final dimensions and properties of the actual product to compare with the predicted design values, the benchmark, and other competitive products. The actual dimensions came very close to the predicted values, especially considering some of the difficulties experienced in the construction phase.

COLLAPSIBLE WHEELCHAIR WHEEL

USER MANUAL
&
INSTRUCTION GUIDE

INTRO:
The Collapsible Wheelchair Wheel is intended for wheelchair use only. Use two Collapsible Wheelchair Wheels. Do not combine with other wheelchair wheels for best use. This wheel fits standard ½-inch wheelchair axles. This wheel is a standard 24-inch diameter. Do not surpass 250 pounds of weight on wheels.

INCLUDES:
This product includes:

- (1) Wheel Hub Section——————————————————————PART 1
- (3) Left Hand Wheel Sections—————————————————PART 2
- (3) Right Hand Wheel Sections————————————————PART 3
- (1) Push Rim——————————————————————————PART 4
- (6) Push Rim Handles——————————————————————PART 5
- (12) Attachment Bolts——————————————————————BOLT
- (1) Portable Wrench———————————————————————WRENCH

ASSEMBLY INSTRUCTIONS:

1. Align location “1” of PART 1 with mating hub hole “1” of PART 2.
2. Insert BOLT and use WRENCH to fasten PART 2 onto PART 1.
3. Repeat STEPS 1-2 for locations “2” & “3”.
4. Align location “4” of PART 1 with mating hub hole “4” of PART 3.
5. Pull back latches on PART 3 while guiding the spokes into their keyways so that PART 2 & PART 3 mesh.
6. Fasten latches into barrel.
7. Insert BOLT and use WRENCH to fasten PART 3 onto PART 1.
8. Repeat STEPS 4-7 for locations “5” & “6”.
9. Insert PART 4 into holes of PART 2 & PART 3.
   OR—
10. Insert (6) PART 5 into holes of PART 2 & PART 3.
11. Fasten PART 4 or PART 5 with (6) BOLTS using WRENCH.

APPENDIX K – Resume

JOSEPH T. FISCHER

9301 W. Chestnut ~ Yakima, WA 98908 ~ fischerjo@cwu.edu ~ 509-654-6369

OBJECTIVE

To solve problems and create new, intuitive solutions using science, engineering, math, and creativity.

To combine my technical skills in engineering and math with my passion for art and design.

EDUCATION

Central Washington University, Ellensburg, WA Jan 2012 – Present

- Mechanical Engineering Technology Major – Technology Specialization
- Mathematics Minor
- GPA: 3.97/4.0 – President's List

Yakima Valley Community College, Yakima, WA Aug 2010 – Dec 2011

- Prerequisites
- Associate of Science Degree
- GPA: 3.87/4.0 - President's List/Dean's List

SKILLS

- **Software:**
    - Word
    - Excel
    - PowerPoint
    - SolidWorks
    - AutoCAD
    - Mathematica
    - Some Java & C++ Programming
- **Machinery:**
    - Manual & CNC Lathes
    - Manual & CNC Mills
    - Drill Presses
    - Welding – TIG, MIG, gas, stick
    - Grinders, saws, and others.
- **Knowledge:**
    - Thermo, Fluid & Technical Dynamics
    - Strength of Materials & Metallurgy
    - Basic & Advanced Machining
    - CAD – SolidWorks, AutoCAD, and others
    - Mathematics – Calculus, Linear, Stats, Differential
    - Some Computer Programming & Electrical Training

- Artistic & Design Training

EXPERIENCE

Inline Steel Fabricators Inc., 2506 S. 26th Avenue, Yakima WA 98903 Summer 2008-09

- Assistant
- Assistant & Forklift Operator

Independent Lawn Care Service Summer 2010

- Lawn Mowing, Edging, and Maintenance
- Plant/Tree Removal and Landscaping

Burkhart Dental Supply, 1705 Creekside Loop, Yakima, WA 98902 Summer 2011

- Service Technician Assistant
- Teamwork & Collaboration with Service Techs & Suppliers

Irwin Research & Development, 2601 W J St, Yakima, WA 98902 Summer 2013-14

- Mechanical Design / CAD Engineer
- Design, Revise, Improve, Predict, Calculate.
- Teamwork & Collaboration with a group of engineers, machinists, & assemblers.

HONORS AND ACTIVITIES

- Consistent Dean and President's List for Academic Achievement Aug 2010 – Present
- Certified SolidWorks Associate Certificate
- Sold award-winning artwork at the Yakima Valley College Student Gallery
- Designed and analyzed structures for family/friends