The City College of New York

Design of a Personal Fire Escape System

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Mechanical Engineering 47300: Senior Design 1

Professor Richard La Grotta

Due Date: 05/12/2020

Executive Summary

The purpose of this project was to design a personal fire escape system that can be used under fire-emergency situations in office buildings. After the event of 9/11 in New York City, engineers realized that there are needs for better escape systems for high-rise buildings. Nowadays, a lot of protocols have been established to evacuate buildings efficiently. However, it still takes a long time to get people out of the building. Therefore, the aim of this project is to design a personal fire escape system where the person can jump off of a window and descend safely at a constant speed of 3 ft/s. The device will operate on no electrical components or equipment to increase reliability for over a long period of time. There are four instructions for the user to follow in order to reach the ground safely. The first instruction is to take out the equipment placed in a hermetic box and put the harness on. Secondly, the user should hook the backpack to the pre-installed hook and hook the harness to the bottom of the backpack as well. Note that it is very important to wear the backpack from the front. Lastly, once the user is hanging outside, they need to pull the brake handle in front of the box to initiate a controlled descent. The maximum height that a person can descend from is 100 ft, equivalent to 10 office building stories and the weight ranges from 50 lbs to 250 lbs. The most important aspect of this project is the braking system that consists of a bell crank lever, springs, brake pads, and a hard-brake. These components ensure that a user weighing within a range of 50 lbs - 250 lbs can descend safely from a maximum height of 100 ft, equivalent to a 10 story building at a rate of 3 ft/s.

Description of Problem

Fire escapes are various types of emergency exits usually mounted outside of the building to provide a method of escaping in the event of a fire emergency. New York City has a dense population with residents living in apartments and connected buildings. Typical fire escapes observed in New York City's residential apartments are stairs outside the building leading down to the ground level. However, the problem with residential stair fire escapes is that it occupies a lot of space and requires maintenance. In addition, most buildings do not have enough space to implement fire escape stairs. The personal fire escape system designed in this report will be easy to use, compact, and will allow the user to descend at a constant speed. With that being said, the primary requirements of the personal fire escape system is listed below.

The requirements for the personal fire escape system are as follows:

1. Clear markings on pre-installed hook and box
2. Portable and lightweight
3. Clear instructions
4. Pre-installed hook and sturdy clasp
5. Adjustable to different body sizes
6. Can handle different weights
7. Rope must be flexible and can withstand a certain amount of dynamic load
8. Must be slow enough to avoid obstructions during descent
9. Rope spools out at a constant speed of 3 ft/s
10. Rope length of 100 feet (equivalent to a building with 10 stories)
11. Fire Proof System

We do not have any interfaces in this design because all the mechanisms are mechanical.

Summary of Solution

The personal fire escape system will be stored in a hermetic box. In case of a fire-emergency, all the user has to do is open the hermetic box, put on the harness, hook the rope to a pre-installed hook in the room using a carabiner and jump out the window. This gives us some of the major components of the fire escape system: carabiner, rope, harness, the pre-installed hook and the braking system device. This section of the report details the procedure of choosing appropriate components of the fire escape system.

1. Carabiner

There are many different types of carabiners that we came across in our design. **Figure A** shows the different types of carabiner shapes in the market as of right now.

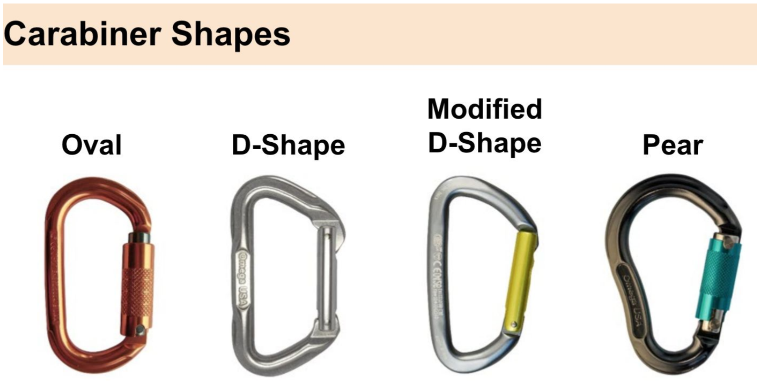
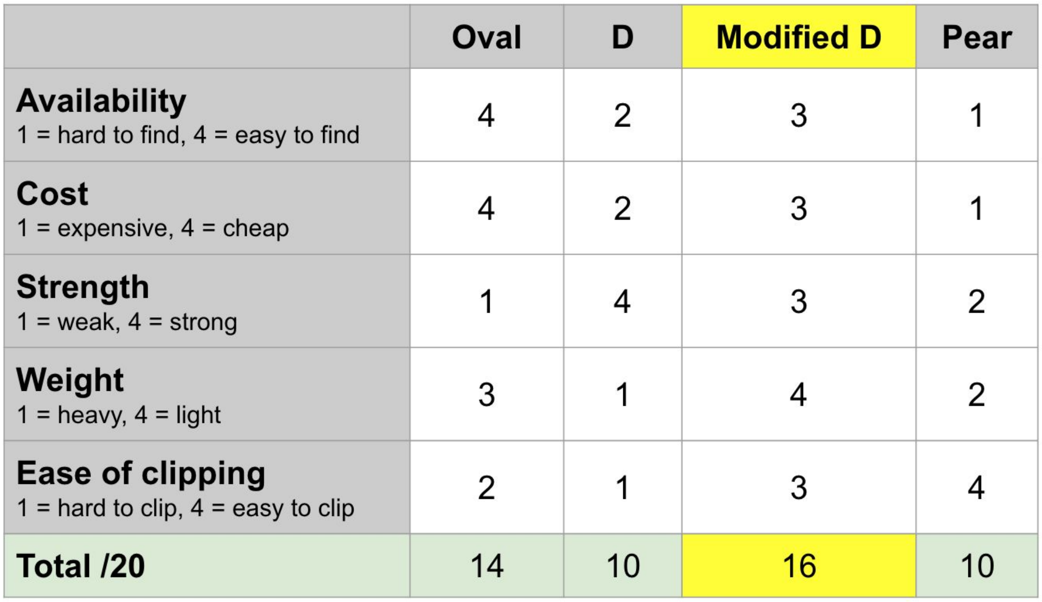


Figure A. Different types of carabiner shapes

To find the best suitable shape of a carabiner, a trade study was conducted and the results are shown below in **Table 1**. As can be seen from **Table 1**, we looked at the availability, cost, strength, weight and ease of clipping to find the best suitable carabiner. Since the Modified-D shape carabiner gives the most possible points, 16, we chose the modified-D shape carabiner for our design.



	Oval	D	Modified D	Pear
Availability 1 = hard to find, 4 = easy to find	4	2	3	1
Cost 1 = expensive, 4 = cheap	4	2	3	1
Strength 1 = weak, 4 = strong	1	4	3	2
Weight 1 = heavy, 4 = light	3	1	4	2
Ease of clipping 1 = hard to clip, 4 = easy to clip	2	1	3	4
Total /20	14	10	16	10

Table 1. Results of the trade study conducted for carabiner shape

Now that we have chosen the shape of the carabiner, the next step was to pick the type of gate. **Figure B** illustrates the different types of carabiner gates used for carabiners.

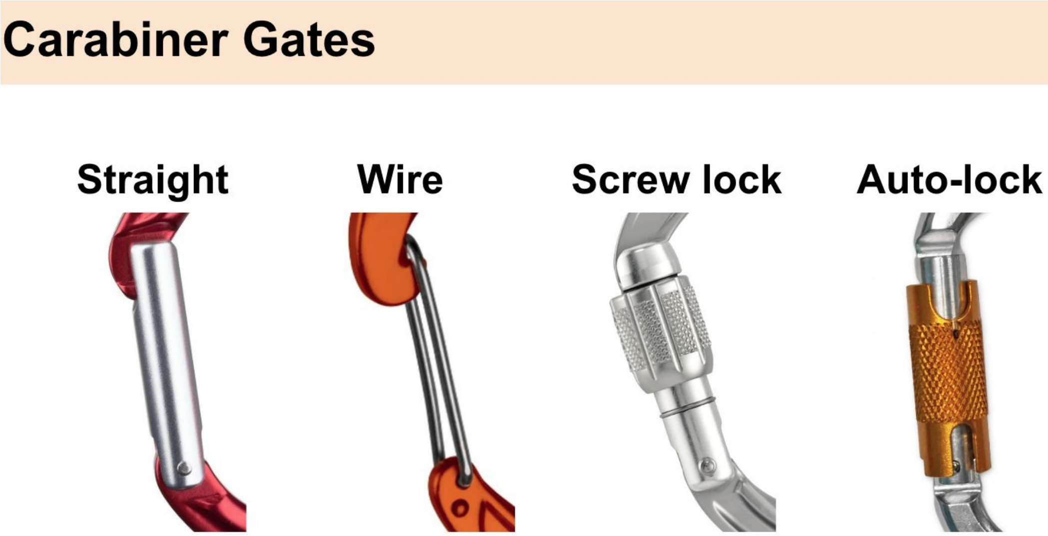


Figure B. Different carabiner gates used for carabiners

To find a suitable carabiner gate, a trade study was conducted again where we examined the availability, cost, safety, ease of opening and ease of locking. As can be seen from **Table 2**, Auto-lock gives the most possible points, 22. Therefore, an auto-lock gate was chosen for our carabiner gate.

	Straight	Wire	Screw	Auto-lock
Availability 1 = hard to find, 4 = easy to find	1	2	4	3
Cost 1 = expensive, 4 = cheap	2	3	4	1
Safety (x3 weight) 1 = not safe, 4 = safe	2 x 3	1 x 3	3 x 3	4 x 3
Ease of opening 1 = hard to open, 4 = easy to open	4	3	1	2
Ease of locking 1 = hard to lock, 4 = easy to lock	N/A	N/A	3	4
Total /28	13	11	21	22

Table 2. Results of the trade study conducted for carabiner gate

To conclude, a modified-D shaped carabiner with an auto-lock is suitable for our personal fire escape system. For the carabiner's material, we will use aluminum because of its light-weight and corrosion-resistant properties.

2. Rope

For our fire-escape system, we need a rope that can handle a weight of up to 250 lbs. However, since there is a high possibility of a dynamic load on the rope, we decided upon looking for a rope that can handle 500 lbs for redundancy. First, we investigated different rope materials as shown in **Figure 1**.

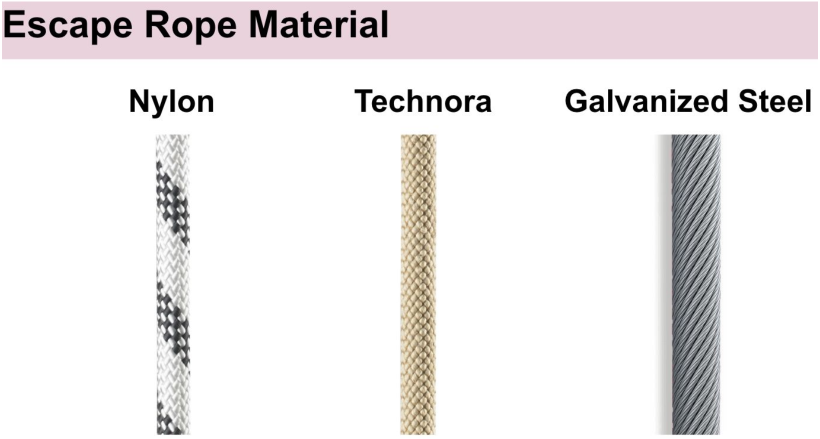


Figure 1. Nylon, Technora, Galvanized Steel are used often as fire escape ropes

Hence, another trade study was conducted to choose a suitable escape rope for our design.

¼ ” Diameter:	Nylon 6	Teijin Technora	Galv. Steel
Availability 1 = hard to find, 3 = easy to find	3	1	2
Elastic Modulus 1 = weak, 3 = strong	2	1	3
Cost 1 = expensive, 3 = cheap	3	1	2
Weight 1 = heavy, 3 = light	3	2	1
Heat Resistance 1 = low , 3 = high resistance	2	3	1
Ease of Attachment 1 = hard , 3 = easy	3	2	1
Total /18	16	10	10

Table 3. Results of the trade study conducted for wire material

As we can see from Table 3, nylon 6 is a suitable material because it earns the most points. In selecting the appropriate diameter of the rope, we had to consider the performance requirements of the rope. The main parameter that defines the performance of an escape rope is its minimum breaking strength. The minimum breaking strength of a rope is the maximum applied load that the rope can withstand before it breaks. From the engineering toolbox website, we found a table of minimum breaking strengths for different diameters of a nylon rope. As mentioned before, one of the main requirements of our rope is that it is able to withstand a weight of 250 lbs. However, the rope withstanding a weight of 250 lbs is just a static condition. In our situation, we also have to account for a dynamic load. We assumed the dynamic load on the rope will be twice the static load of 250 lbs. Hence, we can say that our maximum dynamic load will be about 500 lbs. Using a safety factor of 2 gives us a total operating load of 1000 lbs. Hence, we need to select a rope strong enough to withstand a dynamic load of 1000 lbs. Looking at the table of minimum breaking strengths for different diameters of nylon rope, we decided that we will be using a ¼ - inch diameter rope since its minimum breaking strength is 1486 lbs, which is well above the working load limit of 1000 lbs.

Rope Diameter		Minimum Breaking Strength	
(in)	*(mm)*	*(lb_f)*	*(kN)*
3/16	5	880	3.91
1/4	6	1486	6.61
5/16	8	2295	10.2

Table 4. Engineering toolbox used to choose rope’s diameter

The rope will also have an initial coating that can reduce friction between brake pads and the rope. The purpose of the coating is to have minimum friction between the brake pads and the rope at the beginning of descent. The friction coefficient of the rope coating should be much lower than nylon-rubber (0.76). The reason why we want to apply coating or a lubricant is because we need the user to start descending until they reach a constant speed of 3 ft/s.

3. Harness

The harness is another component that is crucial to our design because it is the first piece of equipment that the user would put on. The harness should be able to withstand a weight of 1000 lbf and should be used under rescue operation which is why we will be buying a "RescueTECH Turnout Escape Harness."

Figure 2. Type of harness used in the design

4. The pre-installed hook

The pre-installed hook needs to be easy to install by the user and should be able to withstand a load of 1000 lbs under operation. We will be using a "Hammock Wall Mount Anchor Hook" that is able to handle 1100 lbs and is made out of 201 stainless steel material. Because this will stay in a room where a fire can spread rapidly, we decided to choose stainless steel as its material since stainless steel is a fire-resistant material.

Figure 3. Pre-installed hook dimensions

5. The Braking System

The braking system is the most essential part of the design. As we did our research on other fire escape systems, we came across many different types of braking systems. Some were manual and the others were automatic. However, we noticed a common theme: every braking system relied on creating enough frictional force to allow a safe descent. A lot of the braking systems are made for the fire-fighters; usually, the fire-fighters are trained to use those braking systems. However, one of our main requirements is that the user will not need training to use this device. This means that the braking system needs to be automatic and should not require user control. In a situation where someone's life is on the line, we wanted to make sure that there are minimal instructions for the user to get out of the building. Therefore, we came across a braking system designed by Skysaver that works very conveniently. This braking system works on a centrifugal brake and lets the user descend at a constant speed. We wanted to purchase and study the existing product in the market. However, the cost of this centrifugal braking system and other centrifugal braking systems were in the range of $1000-2000, which is well above our budget. It was very challenging for us to think of a complete new design that could potentially be cheaper than the centrifugal braking system. However, we did come up with our own braking system that works with the help of a lever, springs, brake pads, a hard brake and a spool of rope. Since this system can be kept in a room for many years, we avoided using electrical components due to an electrical failure.

One of the first steps in designing this braking system was to think how we can slow down a user while descending from the top of a building. After understanding the physics, we drew a free-body diagram as shown below.

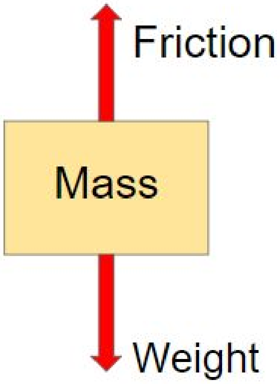


Figure 4. Free body diagram of the falling user

As we can see from the free-body diagram, once the user is falling down, the weight will be the driving force. In order to make sure the user falls down at a slower rate than free-fall rate, we have to add friction to the rope that is attached to the user. According to Newton's Second Law of Motion, the sum of the net forces acting on a body are equal to the mass of the body multiplied by the body's acceleration. Because we want the user to descend at a constant speed, we have to ensure that the acceleration is equal to zero.

$$F_{NET} = ma = 0 \rightarrow \text{Weight - Friction} = 0 \rightarrow \textbf{Weight = Friction}$$

Therefore, we have to make sure that the friction acting on the rope is equal to the user's weight. This led to our first conceptual design as shown below in **Figure 5**.

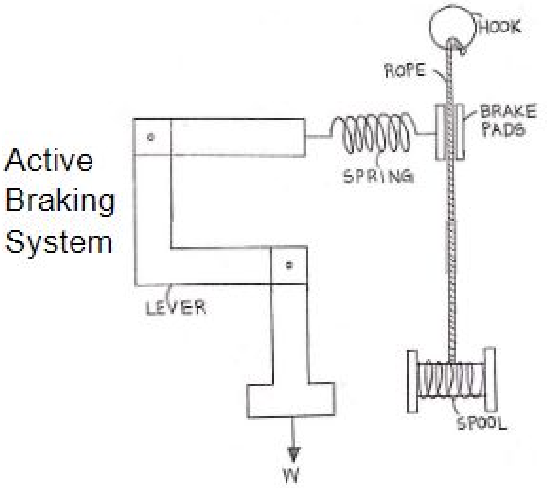


Figure 5. Initial design of the active braking system

As shown above, the braking system works on a lever mechanism. “W” represents the weight of the user and once the user is on the system, the lever’s bottom arm displaces down and the upper arm displaces to the right. The upper arm’s displacement causes the brake pad to compress the rope which creates a force of friction equal to the weight of the user. However, we noticed a flaw with this system. We noticed that once the user jumps out the window, the lever will not displace because the user will already be in motion. The user would just fall down at the free-fall rate; this is not what we want. Therefore, we decided that once the user jumps out, there should be something that stops the user from falling down. If the user is hanging, then the lever mechanism can work. Therefore, we decided to add a hard-brake system as shown below in **Figure 6**.

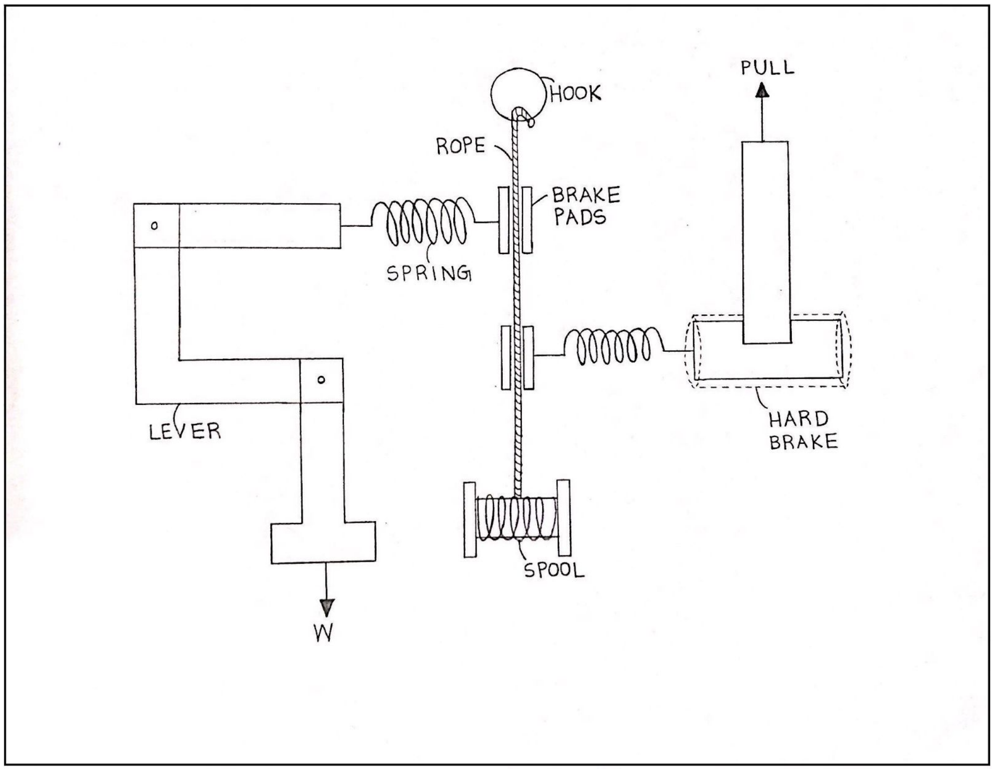
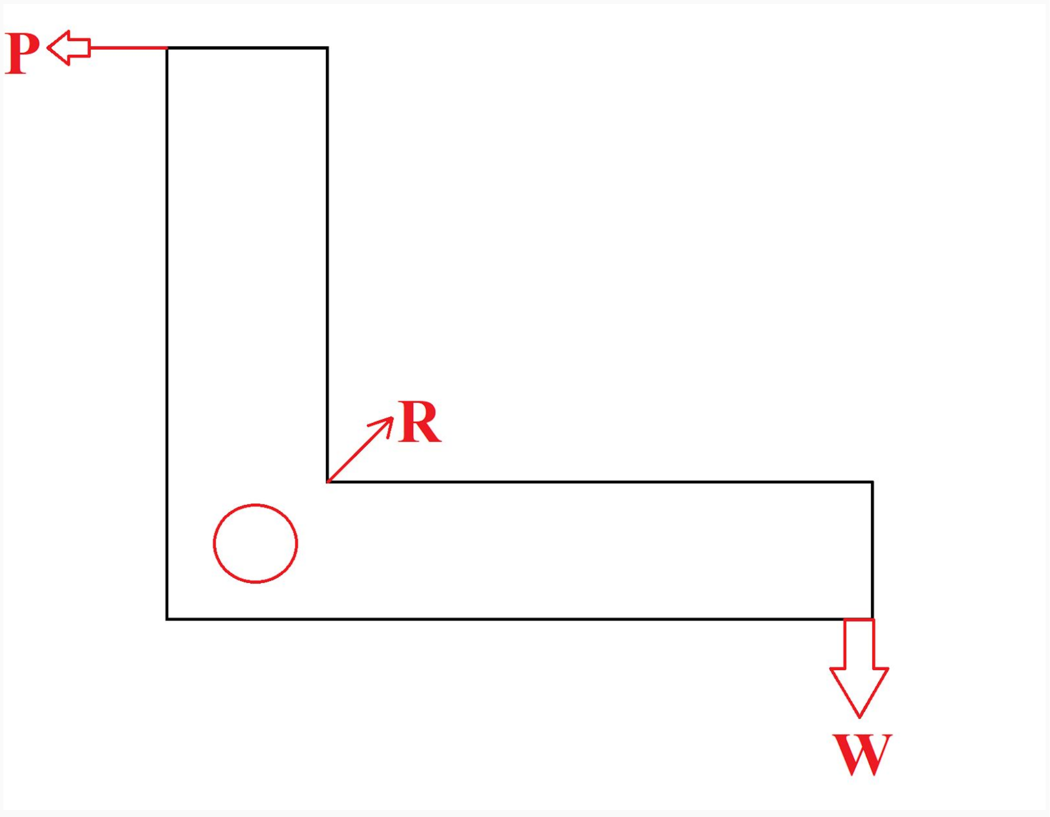


Figure 6. Major components in the final braking system



This braking system is dependent on two brakes. The hard brake is initially activated ensuring that its corresponding spring is compressed. This compression of the spring forces the brake pads to touch each other which creates friction on the rope. Then, once the user hangs on the system, labeled as W, the bell crank lever will move to the right and compress its corresponding spring. This compression causes the upper brake pads to touch, producing a frictional force that is the same as the user's weight. The hard-brake system allows the user and the entire system to be stationary while the upper brake pads are already compressing against the rope, creating friction so that when the hard brake is eventually disengaged by pulling out the block, the user will descend at a rate much slower than the free-fall rate. This controlled rate will also be accomplished with the help of a coating applied on the rope for a certain length. This is explained more in the testing section of this report.

Below is a detailed description of how these components were designed for our braking system.

a) Design of Lever

A right angled bell crank lever is required to be used to transmit the maximum amount of weight a user can apply, 500 lbs (2224 N). The arm lengths of the lever are chosen to be 76.2 mm (3 inches). The lever and pins are made of **Aluminum 6061-T6 T651** which has a yield strength of 255 MPa (**matweb.com**), and the safety factor is chosen to be 5. We chose aluminum 6061 as a material type because it is relatively cheap and lightweight. The permissible bearing pressure is 10 MPa. The lever has a rectangular cross-section and the ratio of width to thickness is 3 to 1. The length to diameter ratio of the fulcrum pin is 1.25 to 1. These numbers were chosen with the help obtained from a textbook: Design of Machine Elements by VB Bhandari.

Figure 7. Forces on the bell crank

Since we are designing this crank for a maximum allowable weight of 500 lbs (2224 N), we can calculate the force P felt by the arm. Because the arms are of the same length, 76.2 mm, we can conclude that force P will be equal to the weight of the user. This is because of a moment balance about point O as shown in **Figure 7**. Therefore, the resultant force will also be equal to the weight of the user because force P is equal to the weight.

$\sigma_{allowable} = (yield\ strength)\ /\ factor\ of\ safety\ =\ 255\ MPa\ /\ 5\ =\ \mathbf{51\ MPa}$

$\tau_{allowable} = (shear\ strength\ at\ yielding)\ /\ factor\ of\ safety$ and according to the maximum shear stress theory, shear strength at yielding is half of the yield strength of the material.

$\tau_{allowable} = (shear\ strength\ at\ yielding)\ /\ factor\ of\ safety = (0.5 * 255 MPa)/(5)\ = \mathbf{25.5\ MPa}$

Using this, we can determine pin dimensions according to the formulas given in the textbook where F_R is the resultant force, $P_{bearing}$ is the bearing pressure, d_1 is the diameter of the pin and l_1 is the length of the pin:

$F_R = P_{bearing}(d_1 * l_1) = 2224\ N\ = 10 * (d_1 * 1.25 d_1) \Rightarrow\ d_1 = 13.34\ mm\ = 0.524\ inches$

$therefore,\ l_1 = 1.25 * d_1 = 16.675\ mm\ =\ 0.656\ inches$

Next, we checked the pin for shear failure:

$\tau_{induced} = F_R /2 * (1/4 * pi * d_1^2) = 8\ MPa$. Because the induced shear stress is lower than the allowable shear stress of 25.5 MPa, this pin will be safe under operation.

Dimensions of lever cross-section:

$M_b = W * 76.2\ mm\ =\ (2224\ N)(76.2\ mm)\ = 169468.8\ N * mm$

$\sigma_b = M_b * y/I\ =\ 51\ MPa\ =\ 169468.8\ * (1.5b)/\ (1/12 * b * (3b)^3)$

$b\ = 13.0\ mm\ = 0.512\ inches\ and\ d = 3b\ =\ 39\ mm\ =\ 1.535\ inches$

Below is an engineering drawing of the lever that we will be using in our system. It should be noted that the bell crank is thicker than what we initially designed it for. This was intentionally done to make our system fixed or else the bell crank was floating around in space. By making the bell crank thicker, it only helps in decreasing the induced normal stress; however, it will increase the weight of the lever. Since safety is a concern, we decided to make it thicker.

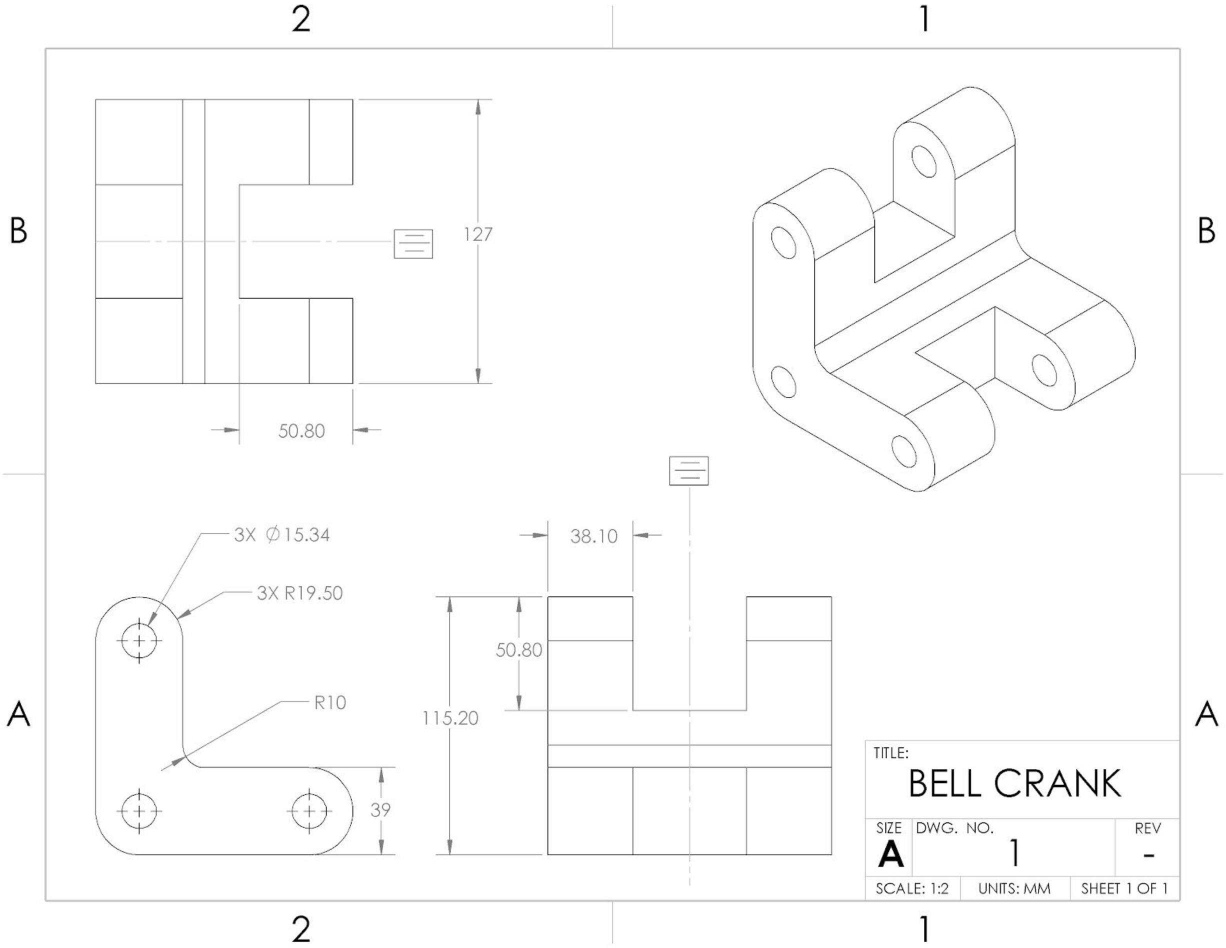


Figure 8. Engineering drawing of the bell crank lever to be used

As we can see the bell crank is not really connected to anything that would allow it to move down and cause horizontal motion. Therefore, we decided to attach arms to the bell crank which would help in creating the motion. The long arm is connected to the bottom of the bell crank and that is the arm which will be moving down once the user is hooked to the braking system. The arm on top of the bell crank is there to provide horizontal motion. The arm on top of the bell crank will be connected to a spring and the spring connects to a brake pad. Once the user is hanging, the horizontal motion will cause the spring to compress and cause friction between the brake pads and the rope, resulting in vertical equilibrium. Below are the engineering drawings of the long arm and top arm to be used. Both arms will also be made out of Aluminum 6061-T6, T651.

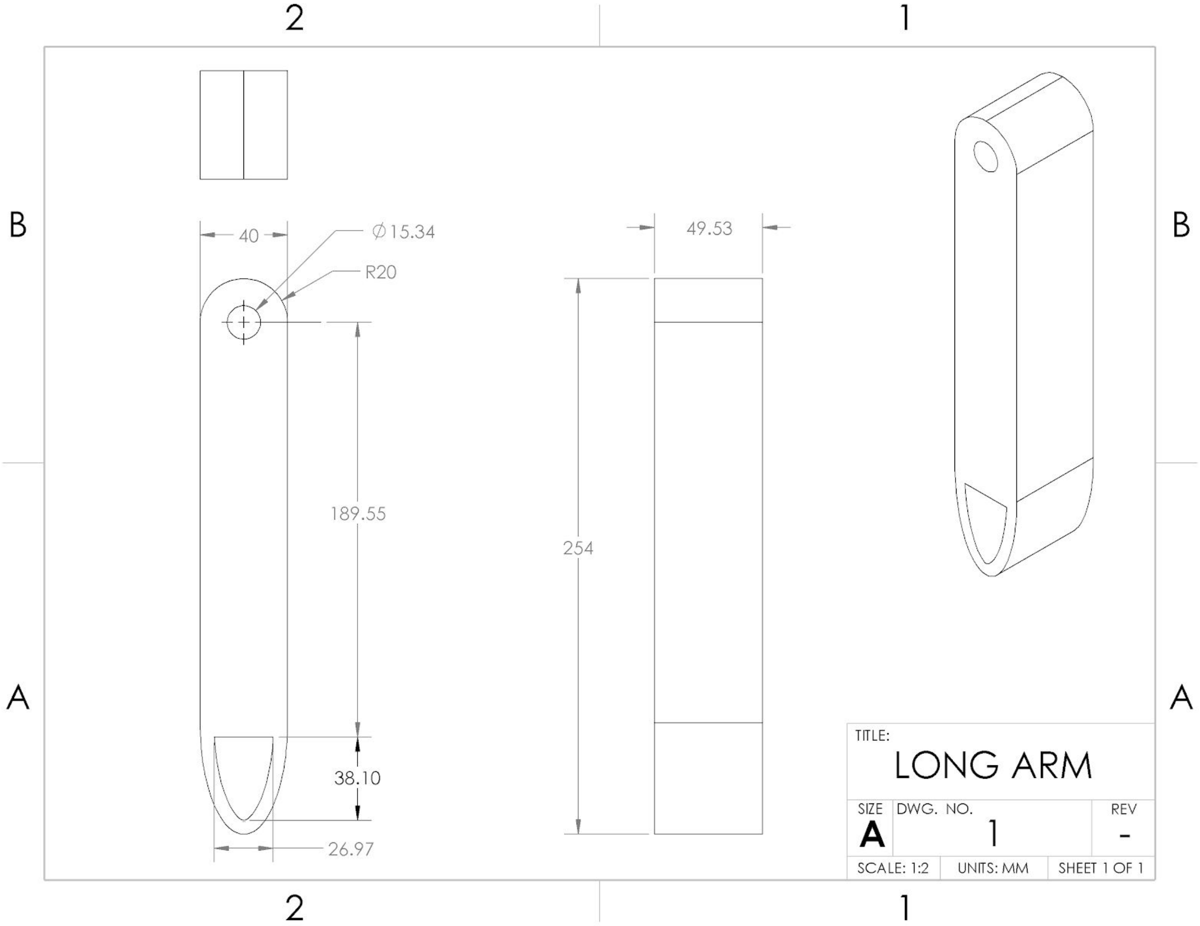


Figure 9. Engineering drawing of the long arm connecting to the weight of user

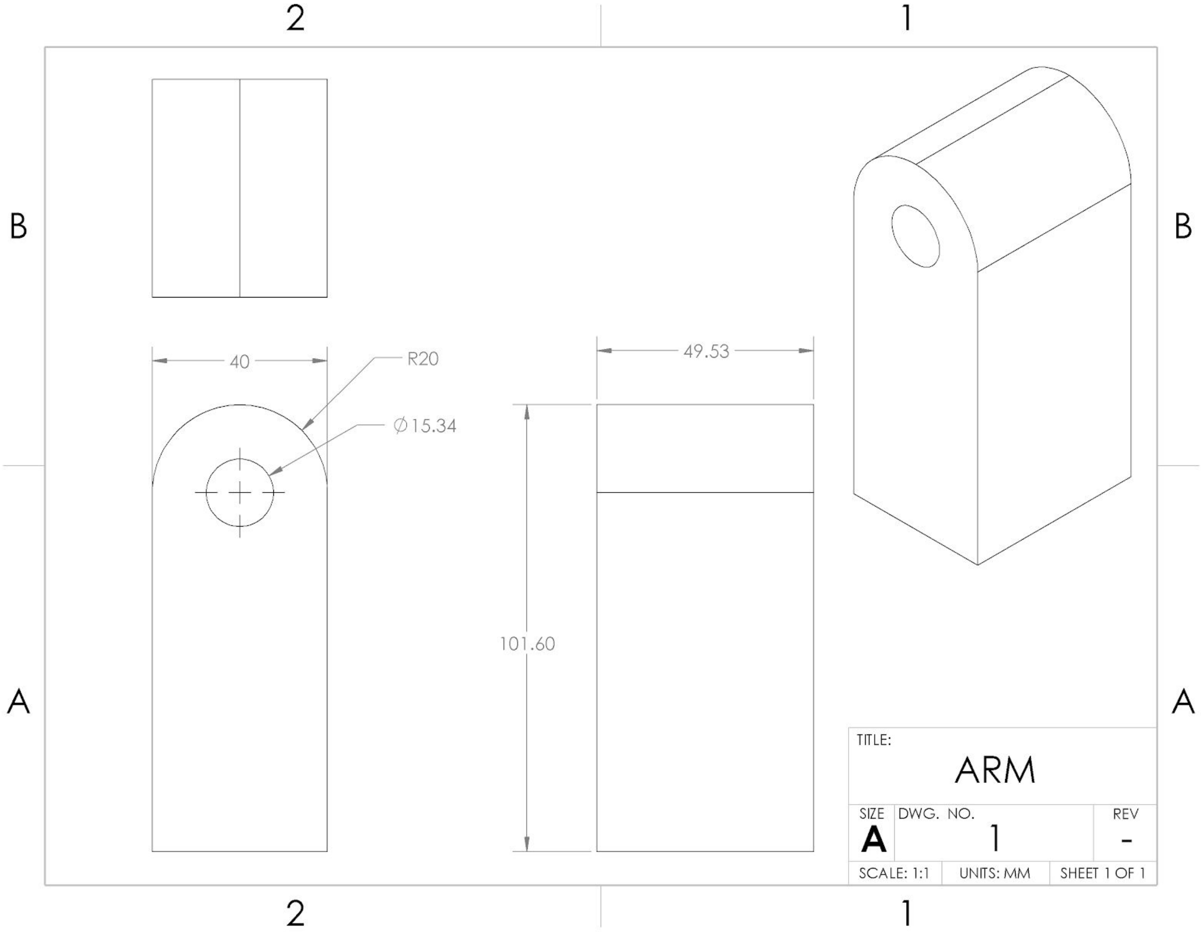


Figure 10. Engineering drawing of the top arm connected to a spring

To fix this system, we will simply purchase pins from McMaster.com. Because we have calculated the dimensions of the lever and analytically shown that this lever will not fail with these dimensions, we decided to run a FEM study to simulate the real-life scenario. The purpose of the FEM study is to conduct a "virtual-test". We want to be able to have an idea of what would happen in the real-life scenario by analyzing a simulation. Every FEM study requires a solid model, therefore, we will be using the model we created for the bell-crank lever.

In order to determine the boundary conditions, we made a bell crank lever out of paper and used a safety pin to fix the lever, as shown in **Figure 11** below.

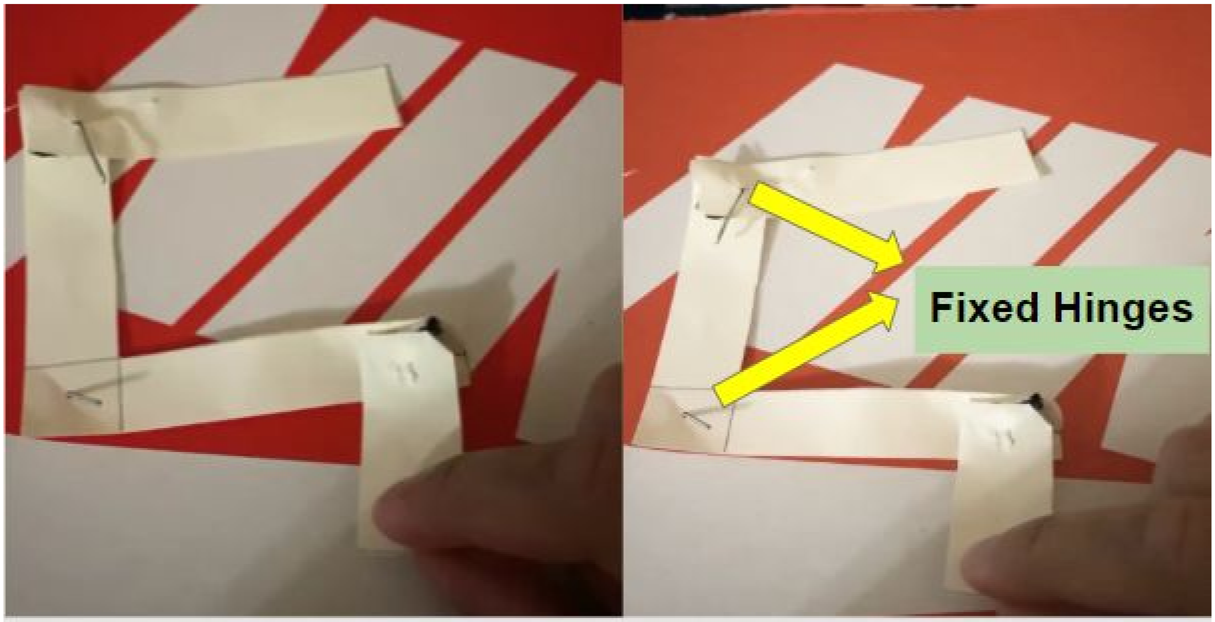


Figure 11. Lever made out of paper to determine boundary conditions

As we can see, once we applied a load on the bottom arm, the lever started to move about the fixed point. To make use of FEM in SolidWorks, we decided to do a static study when the lever is fully translated. During this scenario, we will have two fixed hinges as the top arm of the lever will not be moving. However, the user's weight will still be applied; therefore, there will remain a constant force on the bottom arm. Below are the boundary conditions set up where Force = 500 lbf.

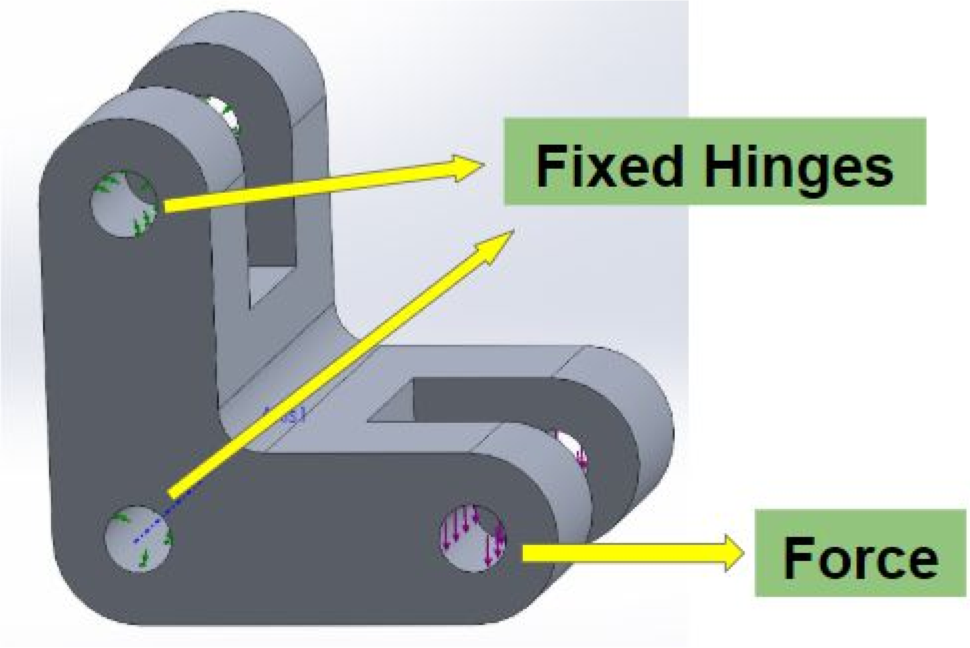


Figure 12. Boundary conditions applied in SolidWorks Simulation

In order to verify whether the boundary conditions are proper, we decided to look at the lever displacement as shown below.

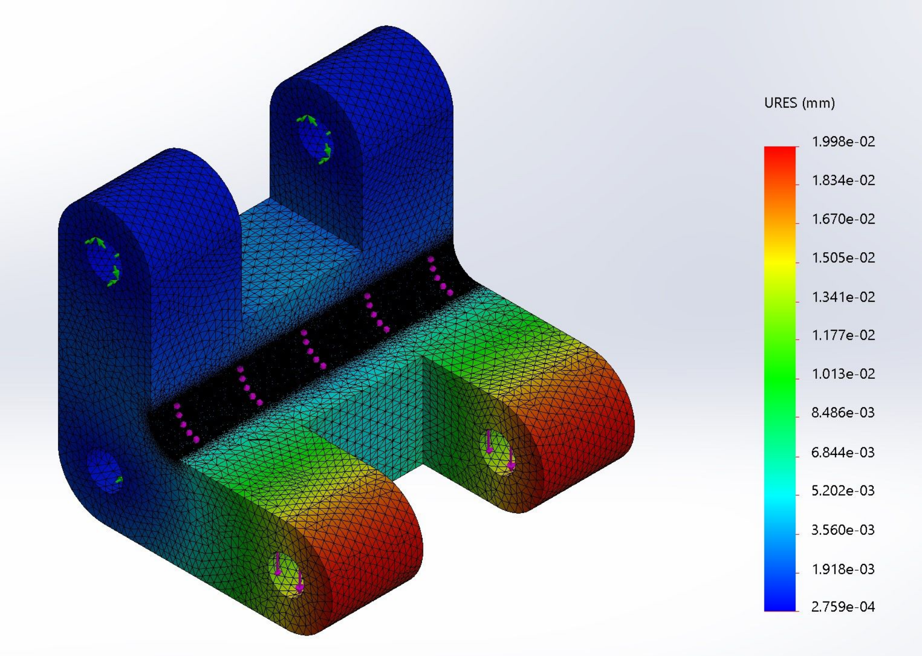


Figure 13. Displacement result from a simulated study

We initially predicted that the maximum displacement will occur at the bottom arm of the lever, since it is at this point where the weight is applied. As seen in **Figure 13**, the results indeed match our predictions. Hence, we have evidence that the boundary conditions are proper and hence our model is valid. Below is also a displacement convergence test.

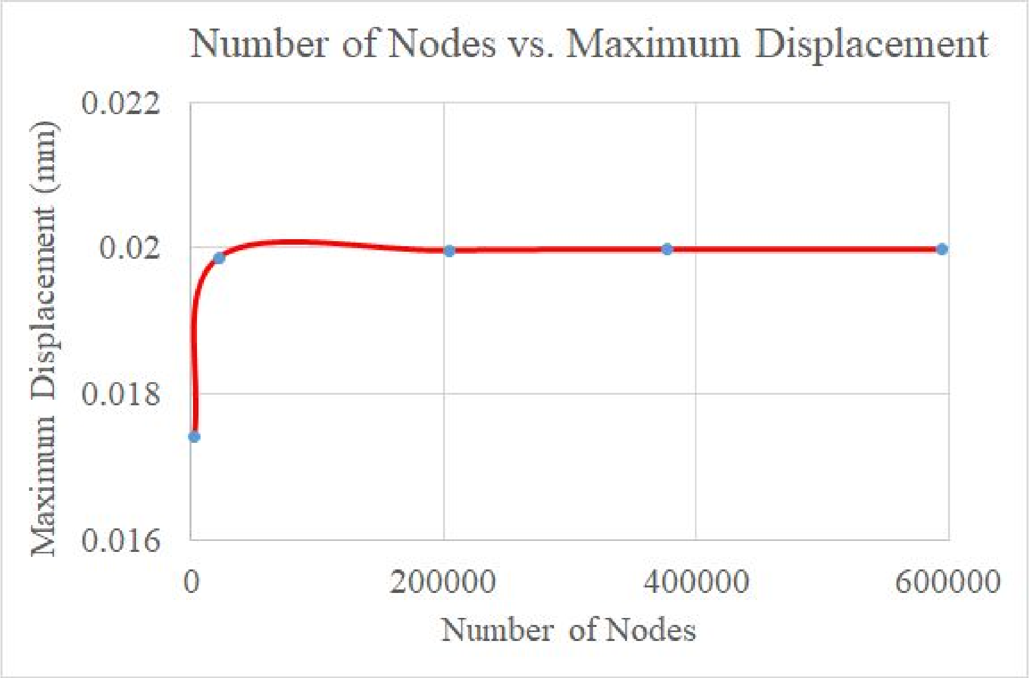


Figure 14. Displacement vs. number of nodes for the simulated study

After analyzing the displacement, we looked at the maximum von-Mises stress to see whether this lever would fail under a load of 500 lbf.

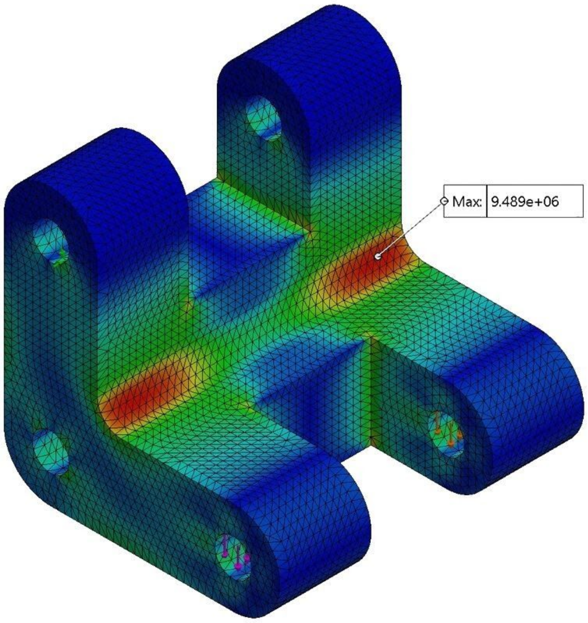


Figure 15. Stress test screenshot from a simulated study

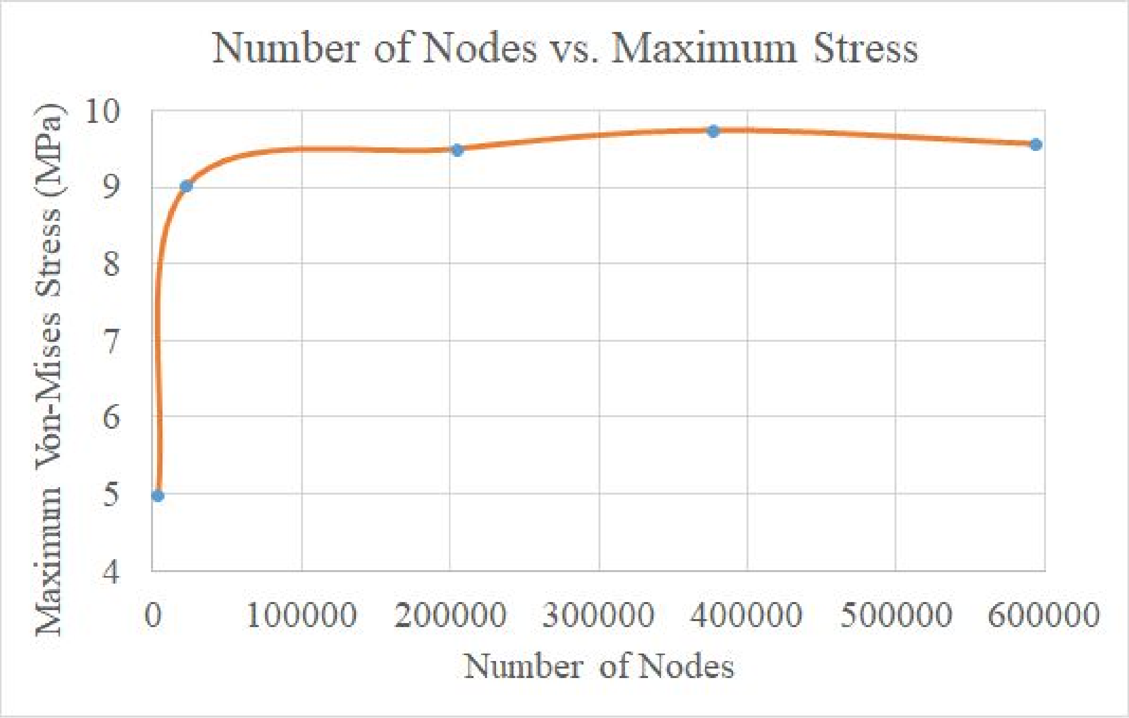


Figure 16. Number of Nodes vs. Maximum von-Mises stress

As we can see from the figure above, the maximum von-Mises stress seems to be converging to 9.5 MPa. We looked at the von-Mises stress because the von-Mises failure theory is used in determining the failure of ductile materials. The von-Mises failure theory states that if the maximum von-Mises stress of a material is equal or greater than the yield strength of the material, the material under the load will yield or fracture. In our case, the lever is made up of Aluminum 6061 T6, T651 which has a yield strength of 255 MPa. Because we used a factor of safety of 5, we can conclude that our allowable/working stress is 255 MPa / 5 = 51 MPa.

Maximum von-Mises stress = 9.5 MPa

Allowable Stress = 51 MPa

Because the Maximum von-Mises stress is lower than the allowable stress, we can conclude that this lever will not yield.

b) Design of Springs

In the design of springs used in the braking system, it is very important to pick a suitable spring because not every user will have the same weight. Therefore, in designing our springs, we looked at a weight range of 50 lbs - 300 lbs.

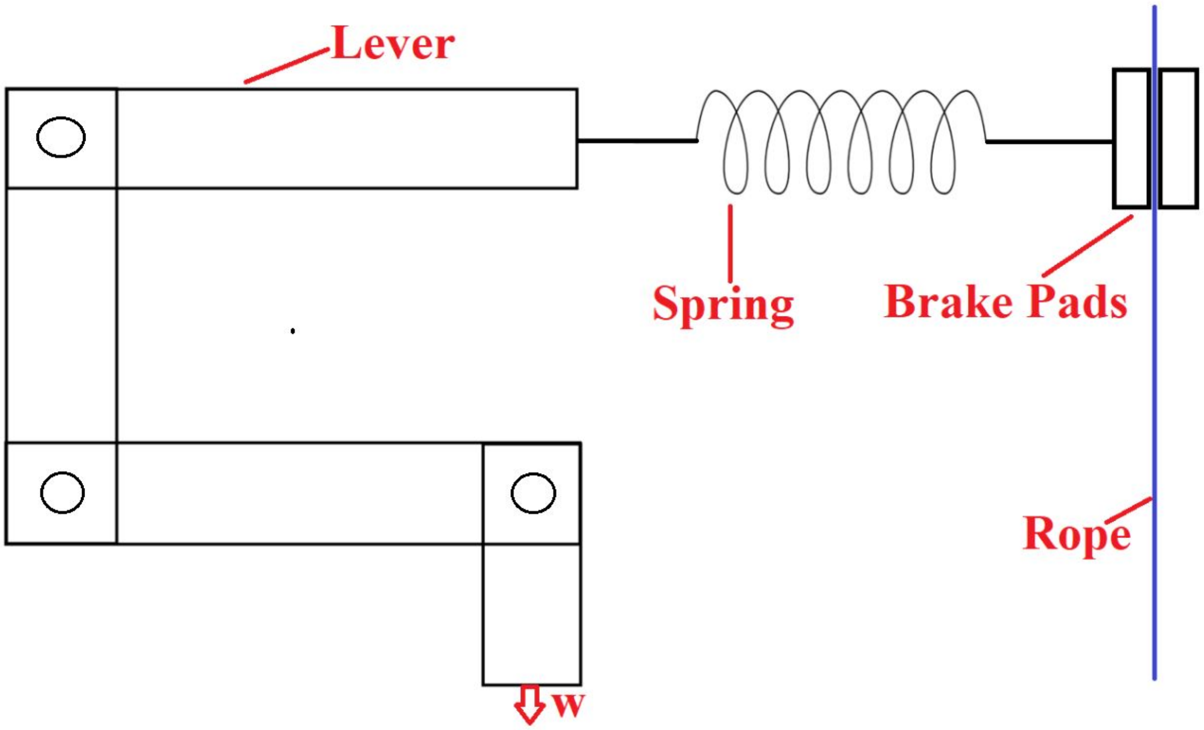


Figure 17. Drawing used to understand spring compression with brake pads

As can be seen in **Figure 17**, the weight of the user, W, needs to be equal to the frictional force produced by the rope and the brake pads to ensure the user does not fall at a free-fall rate. However, there can be users with different weights. Therefore, for our bare minimum weight, 50 lbs, we did the following analysis:

W1 = 50 lbs = 222.4 N, x (chosen spring displacement) = 25.4 mm = 1 inch

Force of friction = μF_N where $\mu = 0.76$ is the kinetic friction factor between nylon and rubber brake pads and F_N is the normal force applied on the brake pads

Therefore, W1 = Force of friction = 222.4 = $\mu F_N = (0.76)(F_N) \rightarrow$ **F_N = 292.6 N**

F_N = 292.6 N = F_{spring} $= k_1 * x = 292.6\text{ N} = k_1 * (25.4\text{ mm}) \rightarrow$ **k_1 = 11.52 N/mm**

W2 = 300 lbs = 1334.5 N, x (chosen spring displacement) = 50.8 mm = 2 inch

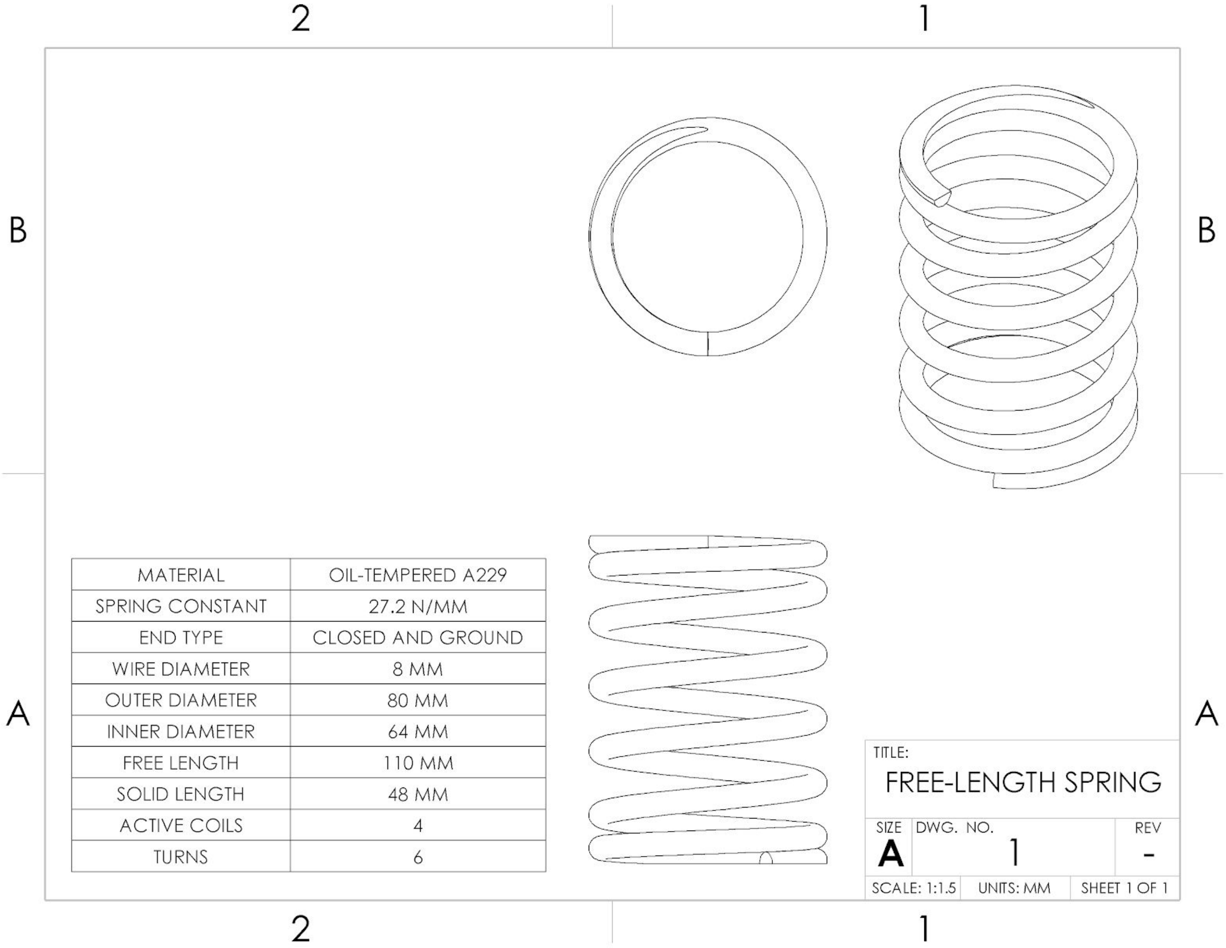
Force of friction = μF_N where $\mu = 0.76$ is the kinetic friction factor between nylon and rubber brake pads and F_N is the normal force applied on the brake pads

Therefore, W2 = Force of friction = 1334.5 N = $\mu F_N = (0.76)(F_N) \rightarrow$ **F_N = 1756.0 N**

F_N = 1756.0 N = F_{spring} $= k_1 * x = 1756.0\text{ N} = k_2 * (50.8\text{ mm}) \rightarrow$ **k_2 = 34.57 N/mm**

$$k_{optimal} = 1/2 * (k_1 + k_2) = \mathbf{23.045\ N/mm}$$

Now, to pick the dimensions of the springs, we used a reliable website:https://www.acxesspring.com/spring-calculator.html. Below is an engineering drawing of the spring.



MATERIAL	OIL-TEMPERED A229
SPRING CONSTANT	27.2 N/MM
END TYPE	CLOSED AND GROUND
WIRE DIAMETER	8 MM
OUTER DIAMETER	80 MM
INNER DIAMETER	64 MM
FREE LENGTH	110 MM
SOLID LENGTH	48 MM
ACTIVE COILS	4
TURNS	6

Figure 18. Engineering drawing of all three springs used in the system

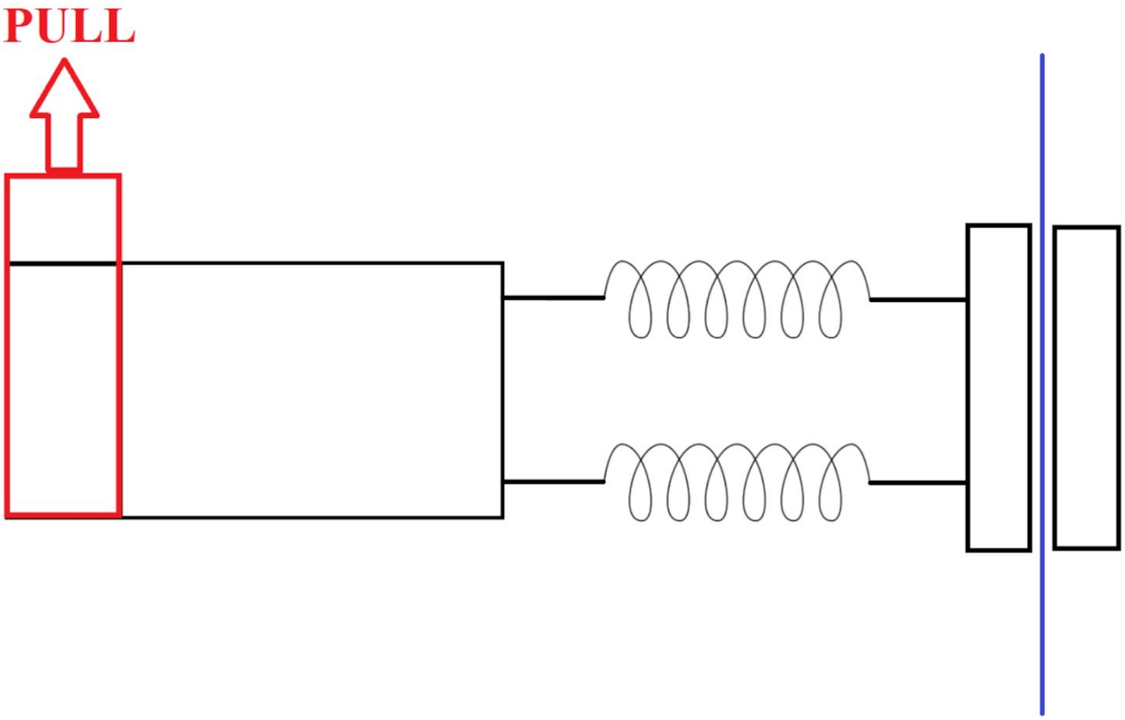


Figure 19. Two springs needed for the hard braking system

Since the hard braking system should be able to prevent any user weight from moving down, we had to make a decision to use two springs. Each spring will provide a force of 250 lbf which totals to 500 lbf. This would ensure that the user is at rest initially. Once the user pulls the block out, the hard brake deactivates and the user can start to move.

Friction force required = 500 lbs (2224.11 N) and x (chosen displacement of spring) = 50.8 mm

$F_{friction} = \mu F_N$ where $\mu = 0.76$ is the kinetic friction factor between nylon and rubber brake pads and F_N is the normal force applied on the brake pads

$$F_{friction} = F_N = 2224.11 = 0.76 * F_N \Rightarrow F_N = 2926.5\ N = F_{spring}$$

$$F_{spring} = k * x = 2926.5\ N = k * (50.8\ mm) = 57.61\ N/mm$$

Now that we are using two springs in parallel, the spring rate can be divided by 2 to give a spring rate of 57.61/2 = **28.805 N/mm.**

Note: The spring rate of the hard brake's spring is fairly close to the spring rate of the spring chosen for the lever. Therefore, we will use the same physical dimensions for all 3 springs.

b.1) Spring cups

To secure the springs to the arms of the lever, we have decided to use spring cups. Below is an image showing how spring cups can be used on springs.

Figure 20. Spring cups required for springs

Now, to connect the spring cups to the lever, we can simply use industrial strength super glue. Below is an engineering drawing of the spring cup that we will be using. We will most likely be purchasing spring cups; however, we needed to model the spring cups to see what size fits our spring and the bell crank lever arm appropriately to our needs.

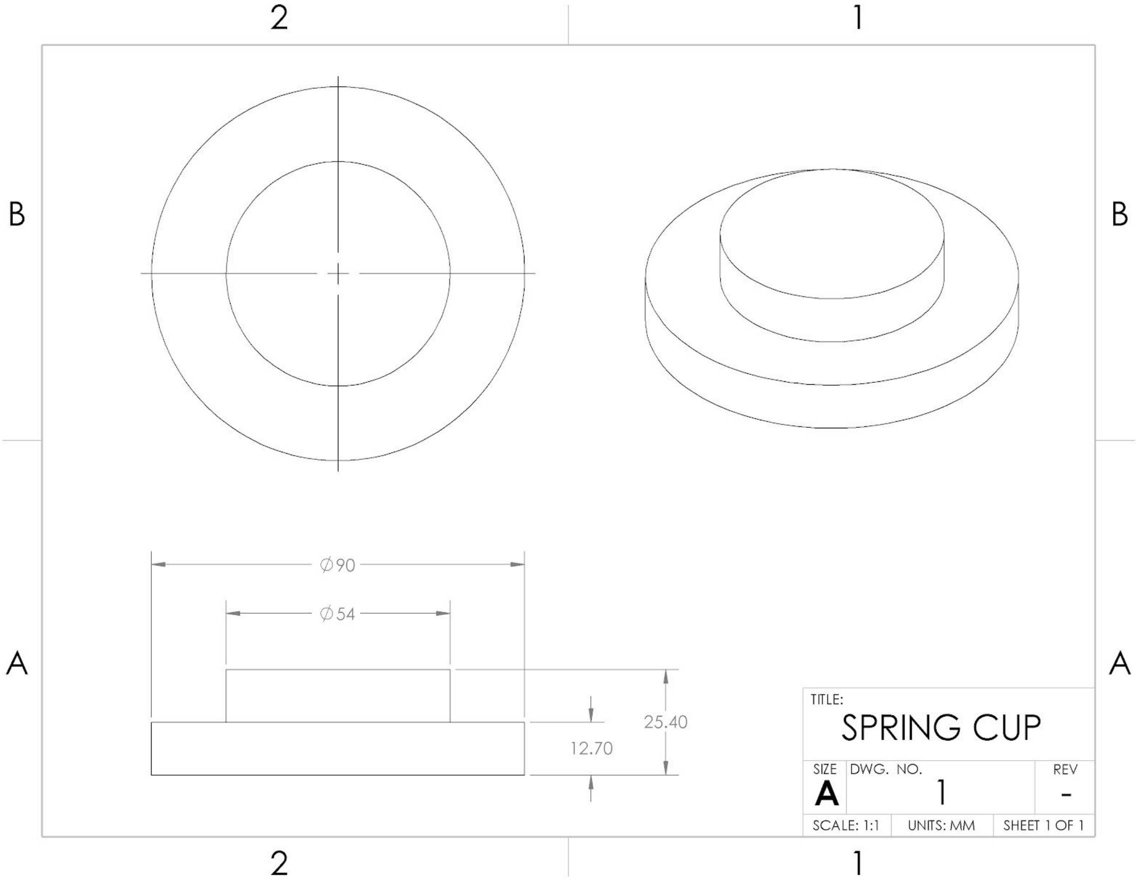


Figure 21. Engineering drawing of a spring cup

c) Design of hard brake system

As mentioned before, the hard brake system was necessary to allow the user to register his/her weight on the system (compress the brake pads connected to the lever before descent begins). As a group, we had an initial design idea of how this hard brake system will operate. Therefore, we proceeded to design a CAD model of our braking system that also consists of a hard brake system. As can be seen in **Figure 6** (major components in the braking system), notice that there is only one spring attached to the hard brake system. However, while working on our CAD model design, we decided that it would be suitable to use two springs instead of one due to sizing issues. Due to this concern, this led us to change the original cylindrical piston shape design into a more rectangular shape to accommodate the two springs connected to the hard brake system. Additionally, we added fillets to the rectangular piston shape to aid in easing the stress as well as help it glide better. After solving this issue, we thought it would be ideal to shift the whole hard brake system to the left since there was extra space to be occupied. Next, we added a rectangular hole on top of the hard brake system by using an extrude cut feature in SolidWorks and added a rail system, which was designed to glide the piece more smoothly that is initially holding the spring compressed and hence the entire system stationary. So the idea is once the carriage in the middle gets pulled out completely, the piston gets pushed back. After this stage, we came across a problem where we were unsure about how to get the user to be able to pull the carriage out to register their weight as this hard brake system was pretty long. After many discussions with our group members, we thought it would be ideal to rotate the whole hard brake system 90 degrees to overcome this hurdle. Now that we flipped the hard brake system 90 degrees in SolidWorks, we got rid of the fillets because they were creating an obstacle. By tackling this issue, we were able to not only decrease our overall height but were also able to make it more accessible because the pulling mechanism was at a lower height as well. Another difficulty we came across was that the carriage could not be the full width of the piston since the user needed to pull the carriage out horizontally and a full width carriage would be too sizable to pull it out completely. Therefore, we adjusted the rail in a way that would stop the carriage in the middle. Finally, we attached a rope and a handle to pull out the carriage. Below is an engineering drawing of a carriage, piston, rail, brake handle, cylinder, horizontal guide, and rope guide, respectively.

1. *Carriage*

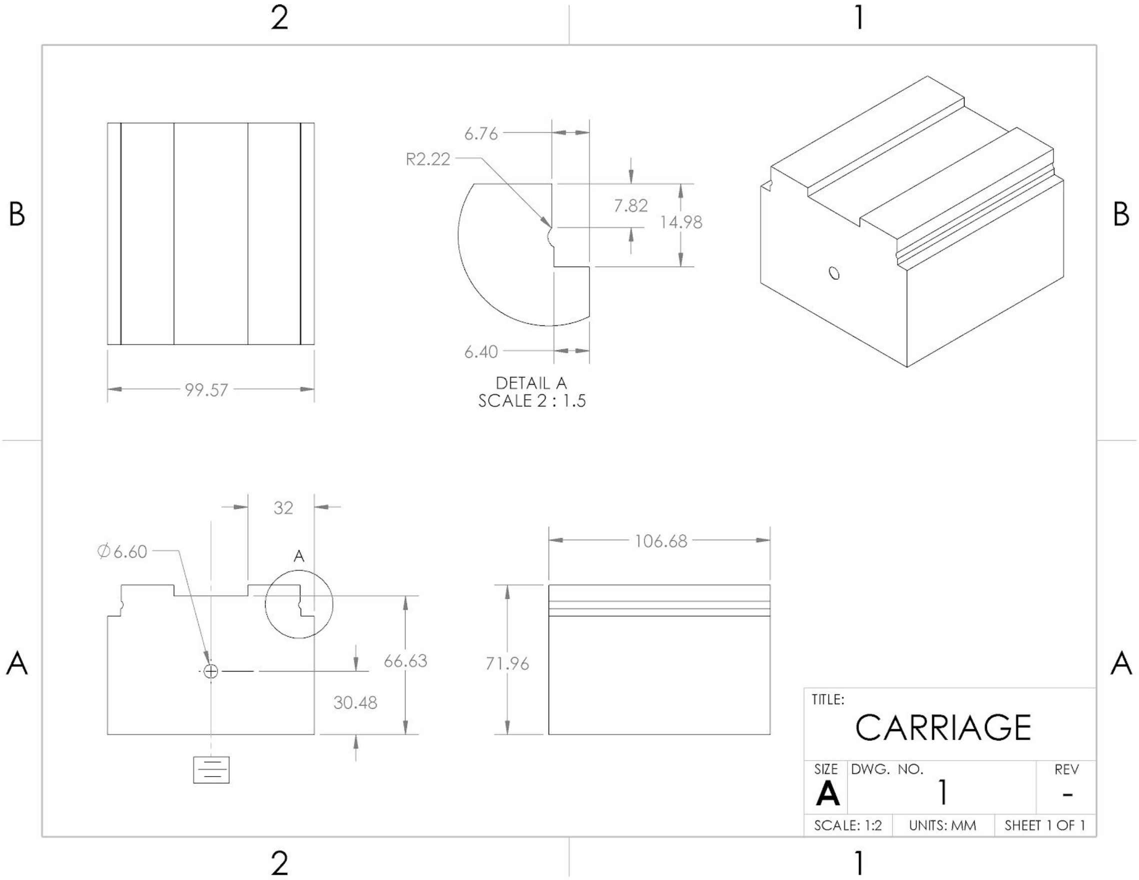


Figure 22. Engineering Drawing of Carriage

2. *<u>Piston</u>*

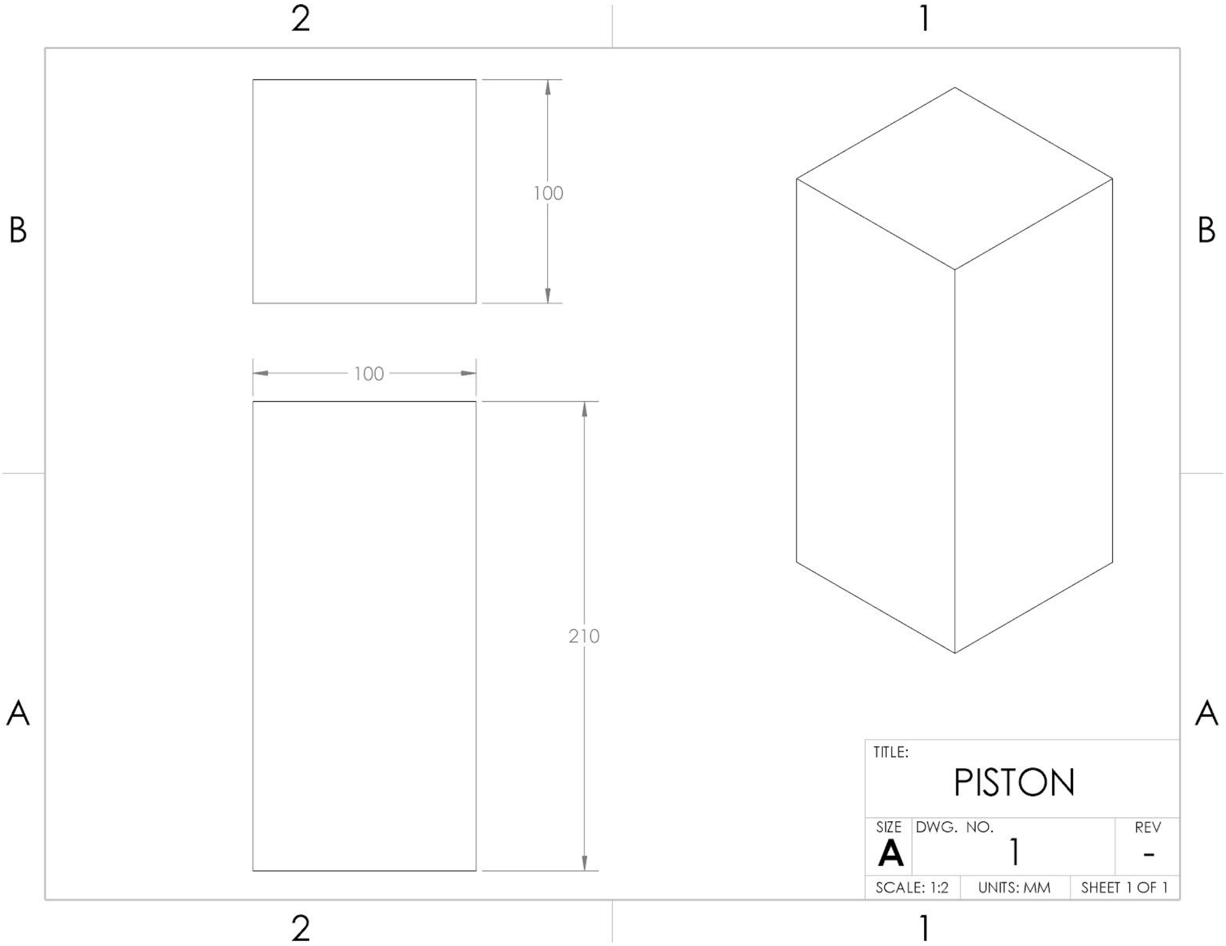


Figure 23. Engineering Drawing of Piston

3. *<u>Rail</u>*

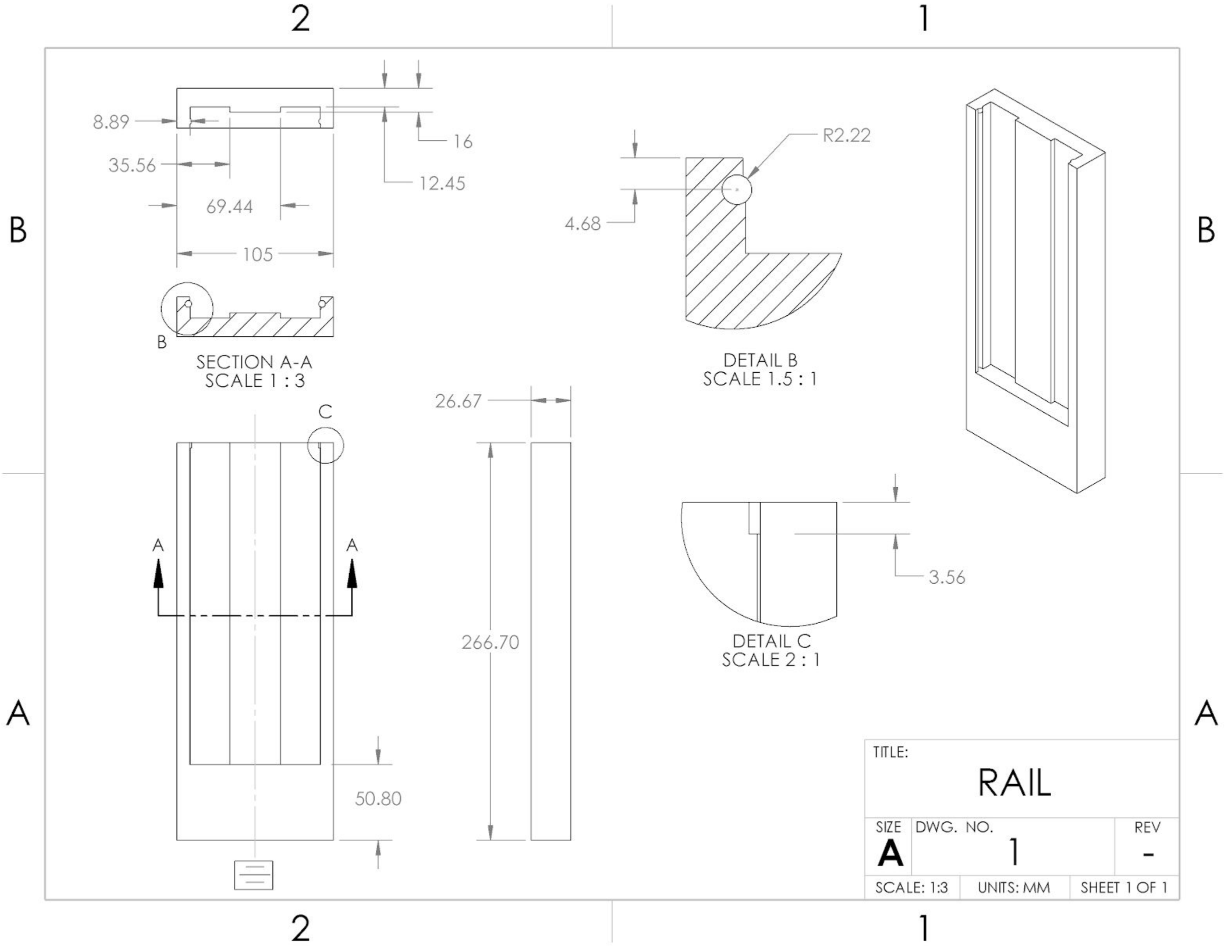


Figure 24. Engineering Drawing of Rail

4. *Brake Handle*

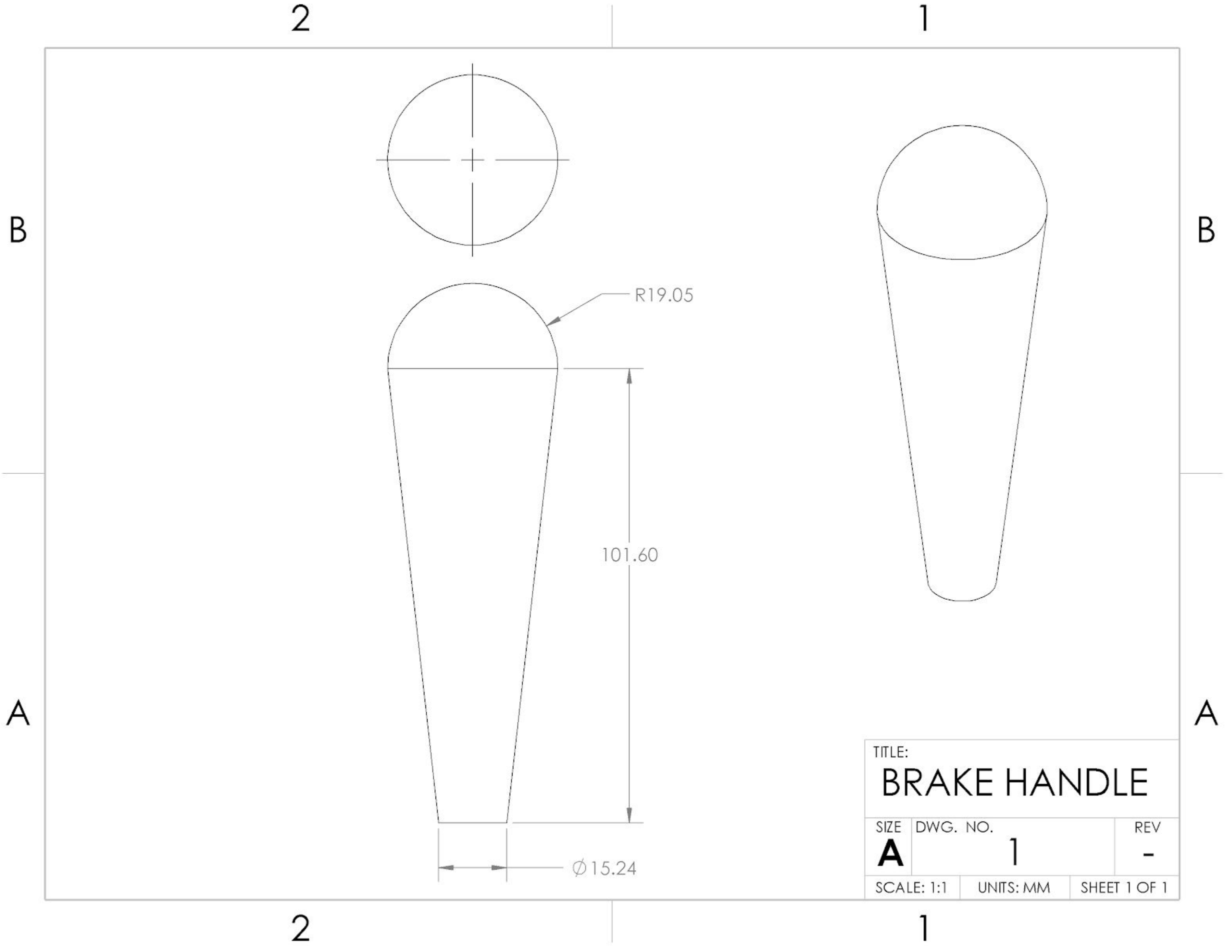


Figure 25. Engineering Drawing of Brake Handle

5. *Cylinder*

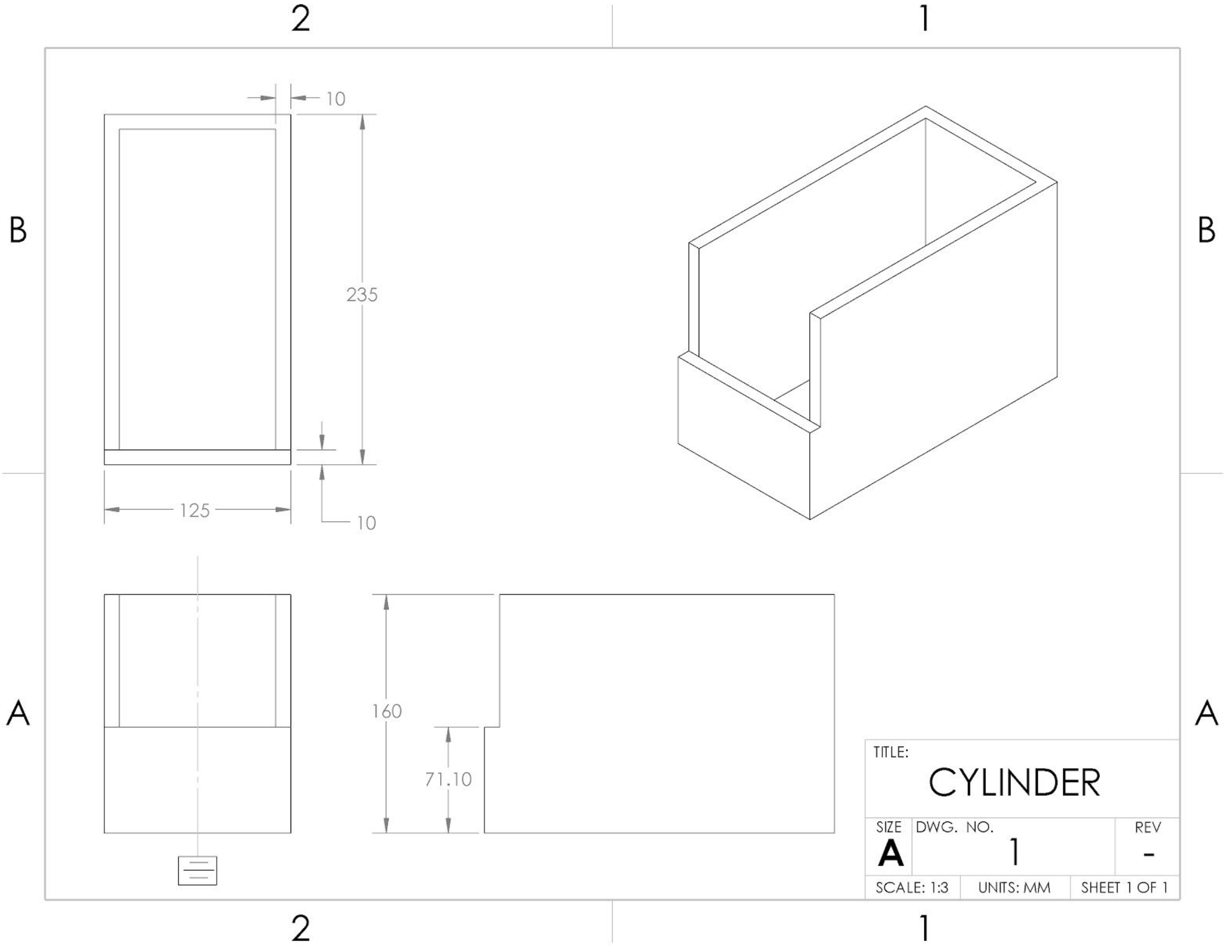


Figure 26. Engineering Drawing of Cylinder

6. *Horizontal Guide*

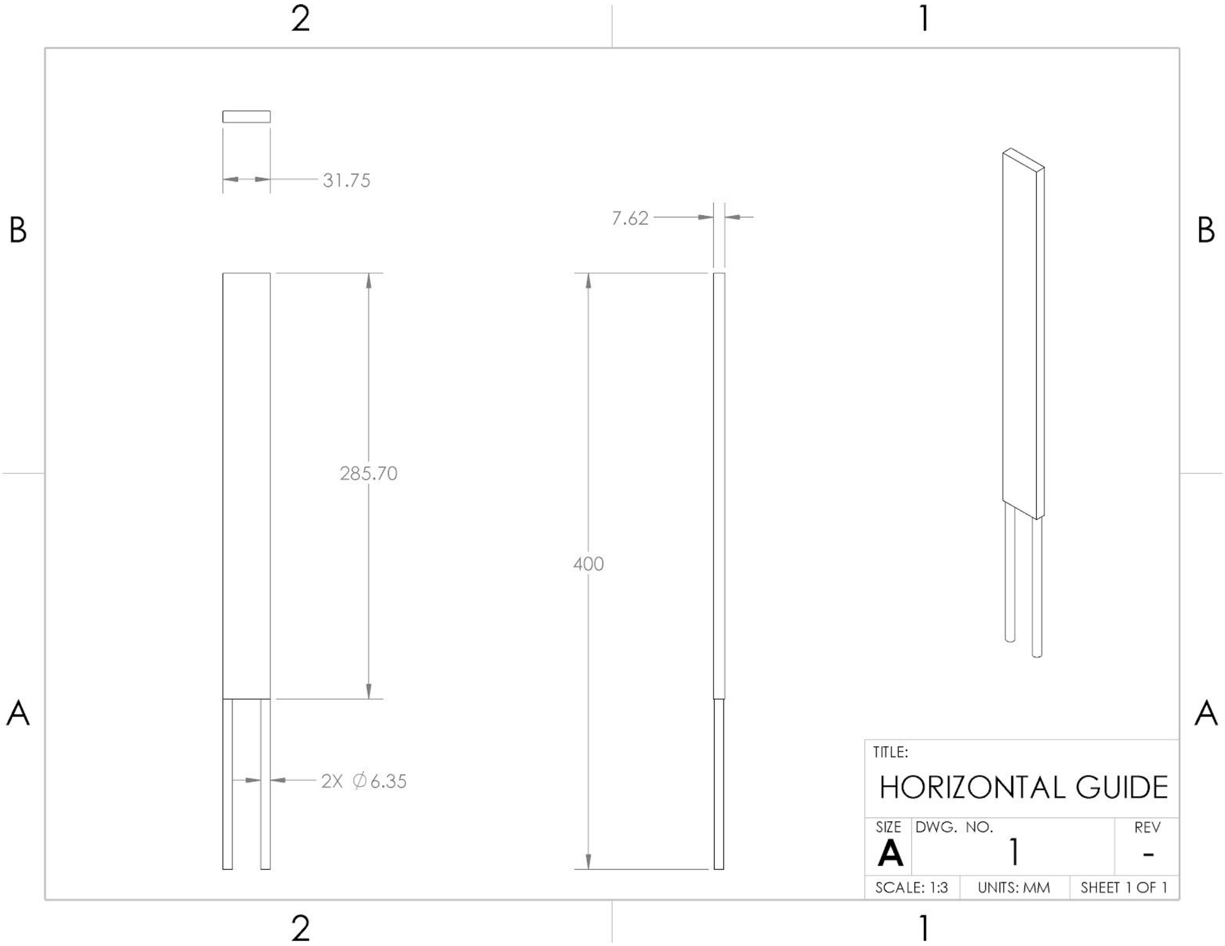


Figure 27. Engineering Drawing of Horizontal Guide

7. *Rope Guide*

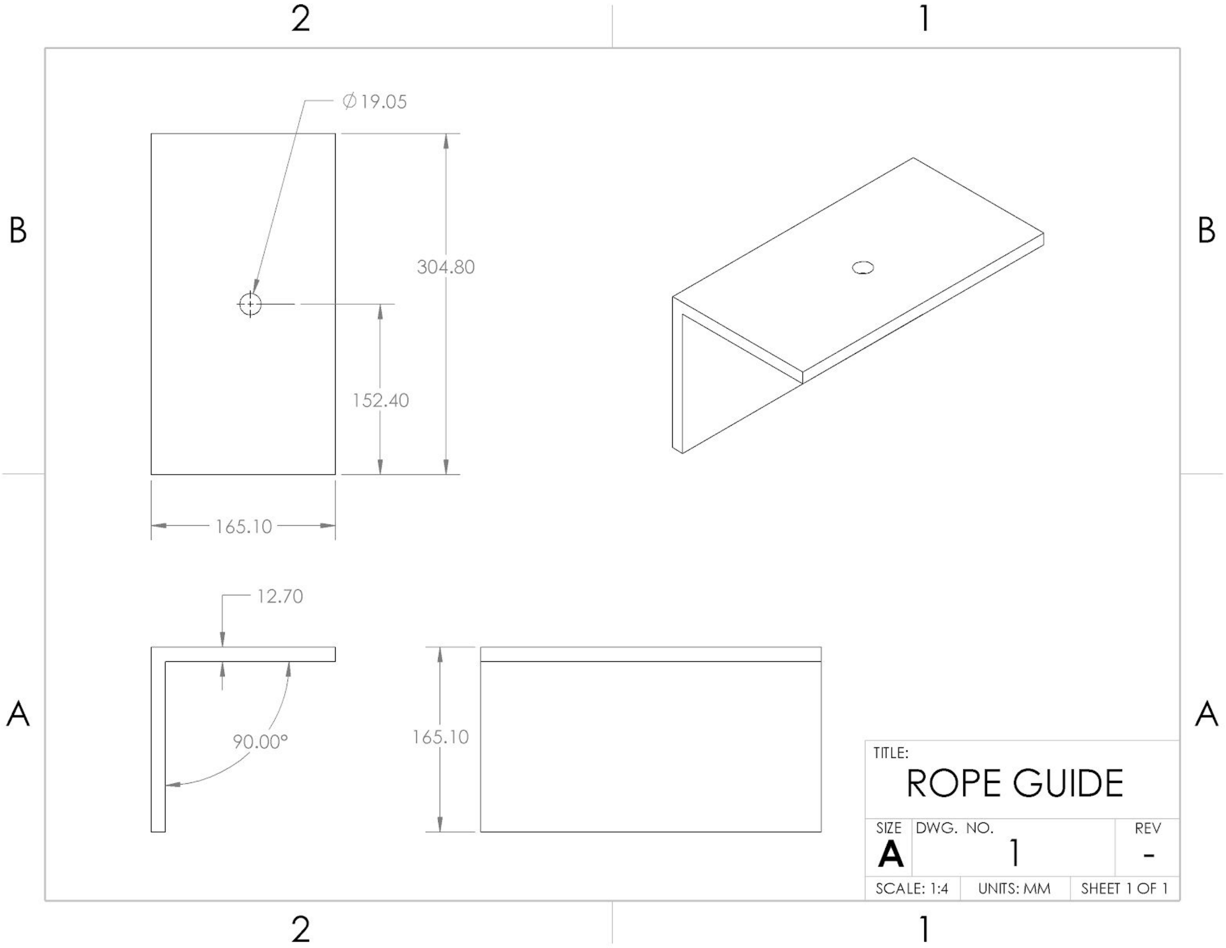


Figure 28. Engineering Drawing of Rope Guide

d) Design of Brake Pads

Brake pads are composed of backing plates with friction material bound to the surface that faces the rope. If we observe the diagram shown above, we will have 3 brake pads. The brake pads are designed to resist brake fade, apply appropriate friction, and perform well under strenuous conditions. The material selected for the brake pad is organic. Organic brake pads are composed of materials such as rubber and fibers. In addition, organic brake pads are inexpensive, can resist brake fade, and perform well under heat. The following three are the brake pads used in the design:

1. *Brake Pad Wall*

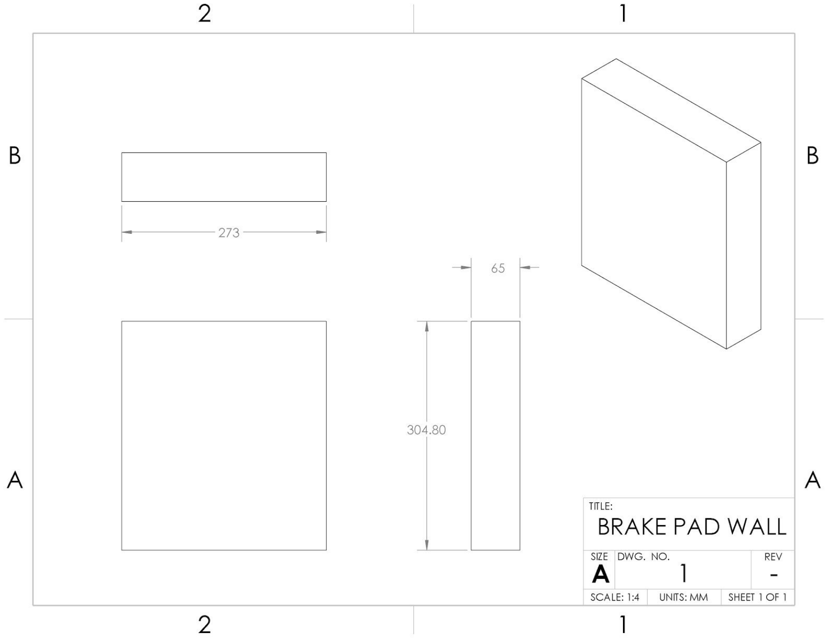


Figure 29. Engineering Drawing of Brake Pad Wall

2. *Weight Brake Pad*

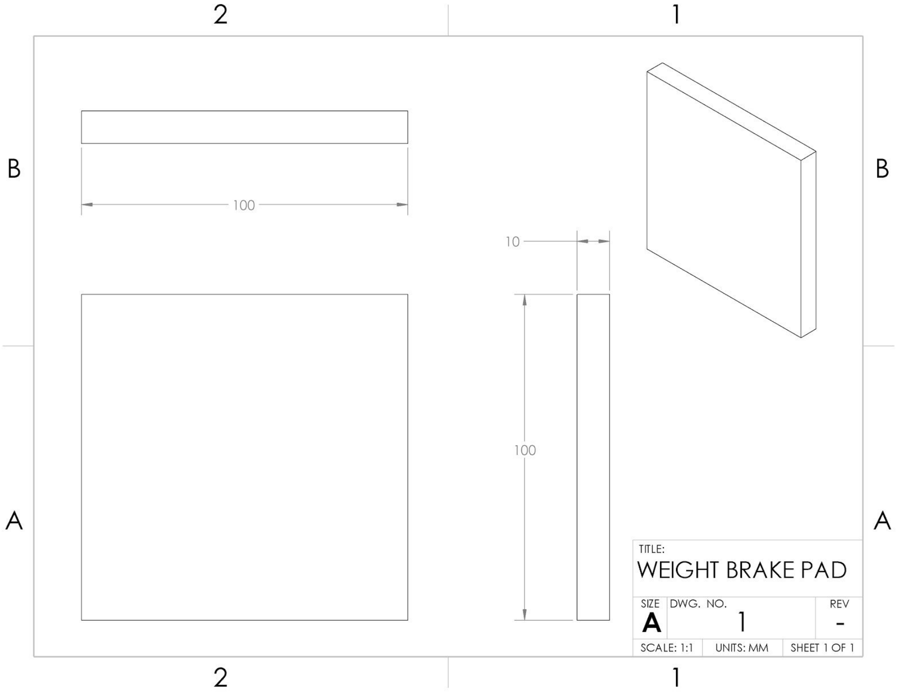


Figure 30. Engineering Drawing of Weight Brake Pad

3. *Hard Brake Pad*

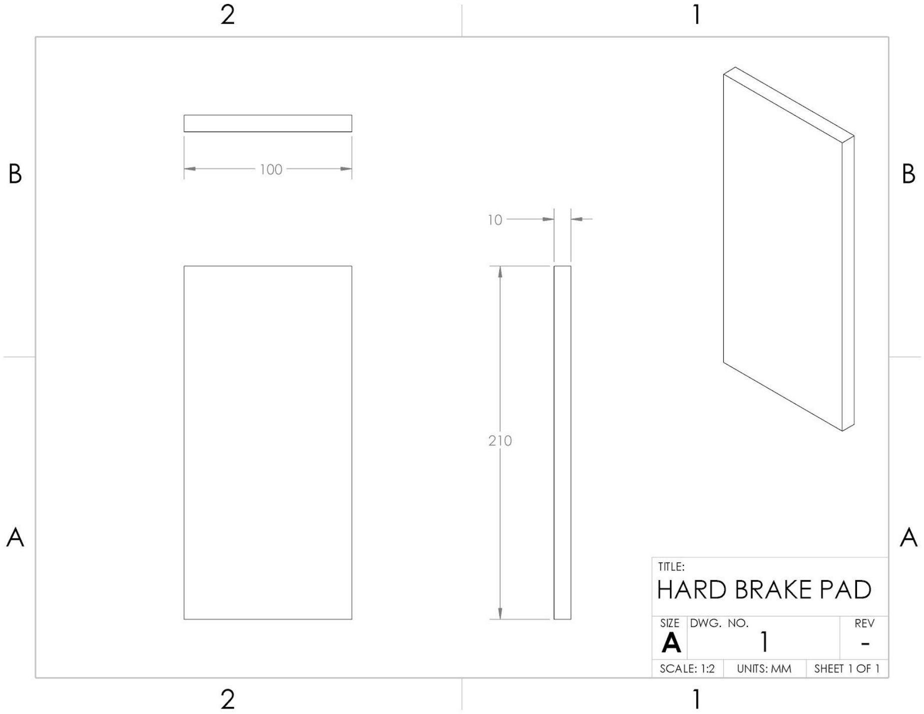


Figure 31. Engineering Drawing of Hard Brake Pad

Four commonly used brake pad materials are Ceramic, Organic, Semi-Metallic, and Non Metallic

	Ceramic	**Organic**	**Semi Metallic**	**Non Metallic**
Availability 1 = hard to find, 4 = easy to find	3	4	2	1
Cost 1 = expensive, 4 = cheap	1	4	3	2
Loudness 1 = Loud, 4 = Quiet	4	3	1	2
Fatigue 1 = wears down fast, 4 = hard to wear down	4	3	2	1
Fireproof 1 = bad performance, 4 = good perf. Under heat	2	3	4	1
Total /20	14	**17**	13	7

Table 5. Trade study conducted to choose a suitable material of brake pads

e) Design of Spool

It is important that we design a spool with the required dimensions so that our 100 feet, 0.25-inch diameter rope will fit properly on the spool. From our online research, we were able to find an equation that calculates the length of the rope that can be winded on a spool with given dimensions. However, since we are choosing the length and diameter of our rope, we had to perform trial and error calculations (using iterations) in order to determine the spool dimensions which will make our rope fit properly on the spool.

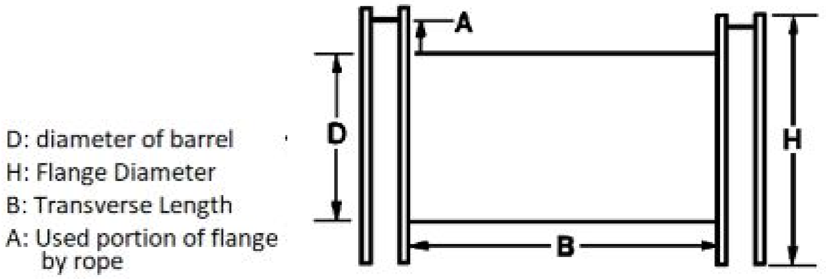


Figure 32: Parameters need for spool design

$Rope\ Length,\ L = (A + D) * (A * B) * K,\ where\ K = 3.29\ for\ a\ 1/4\ inch\ rope$

By trial and error, we obtained the following dimensions:
$B = 7\ inches,\ H = 5\ inches,\ D = 2.5\ inches\ and\ A = 0.5 * (H - D) = 1.25\ inches$

Therefore, **L = 108 feet.** With the calculated length being 108 feet, we deduced that this spool size should certainly fit a 100 feet rope. Below is an engineering drawing of the spool to be used.

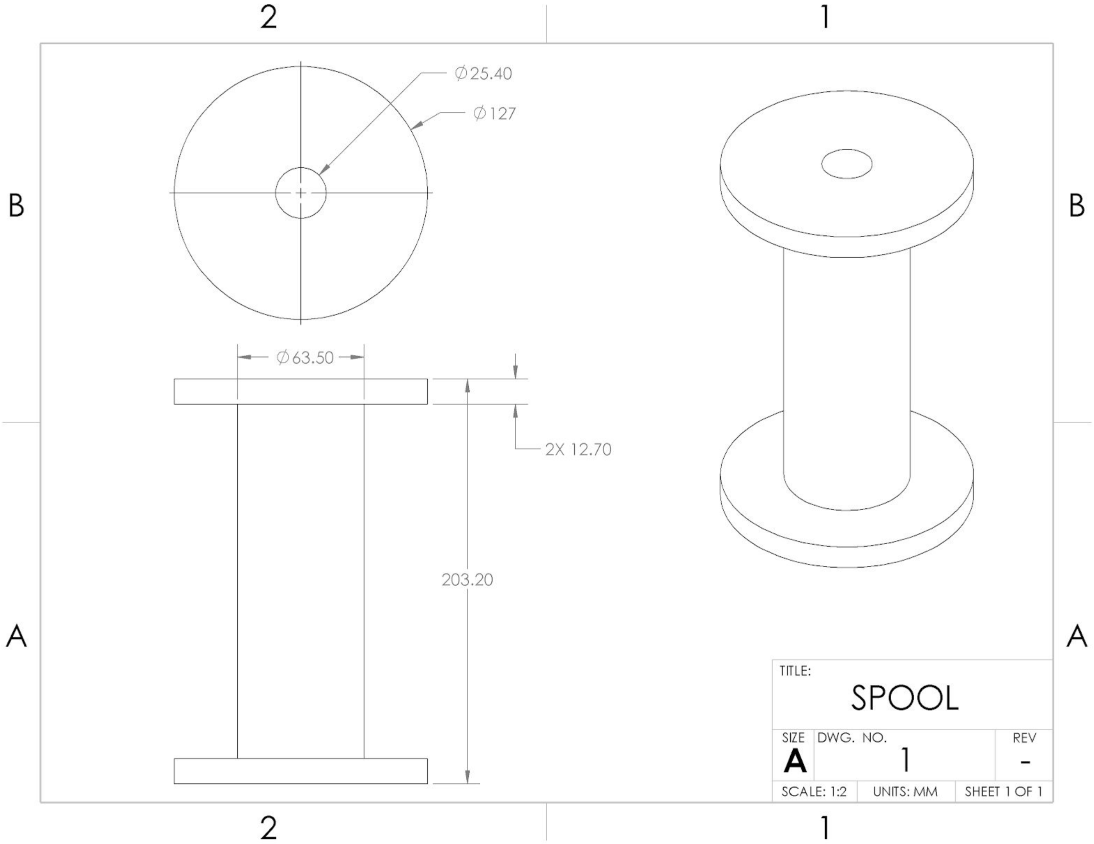


Figure 33. Engineering drawing a spool used to store 100 feet of rope

f) Design of the housing for braking system

Below are the engineering drawings of the housing that will be used for the braking system. The material will be Aluminum 6061 T6, T651 for lightweight benefits. The overall dimensions of the casing will be 482.60 mm x 400 mm x 304.80 mm.

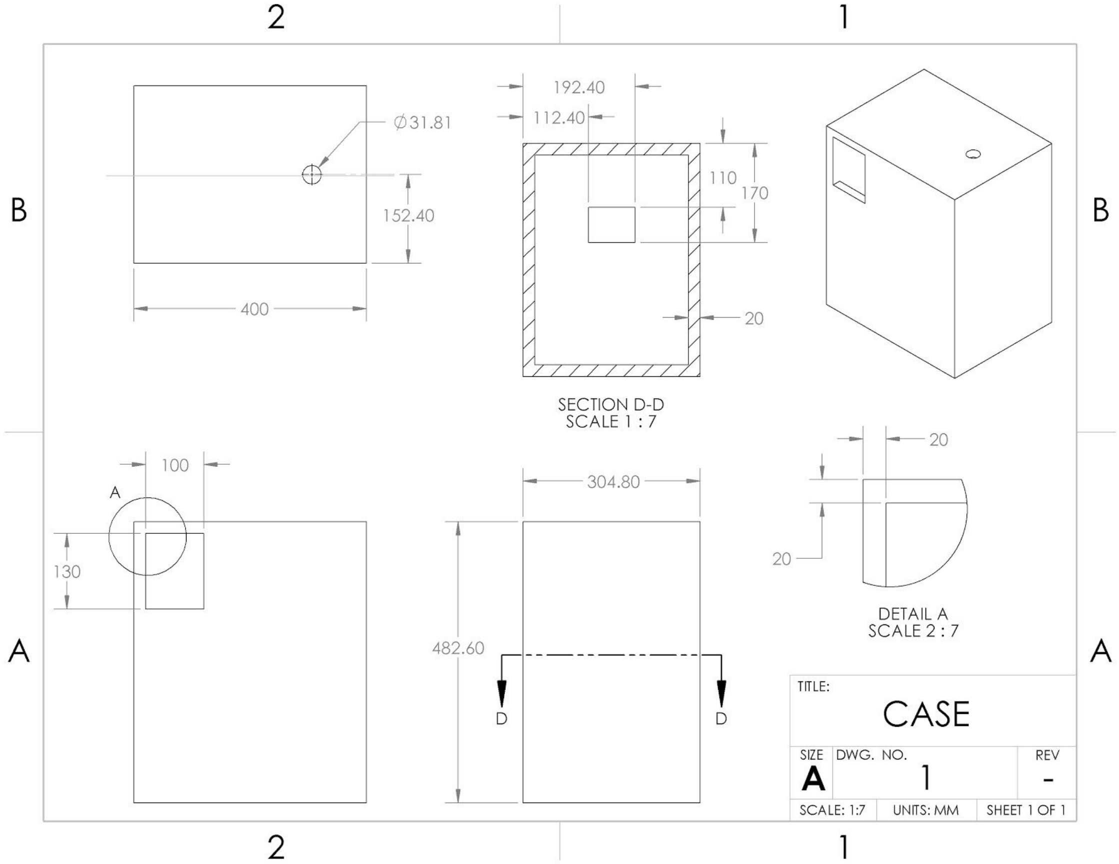


Figure 34. Engineering drawing of the housing used for braking system

Summary of the Braking System

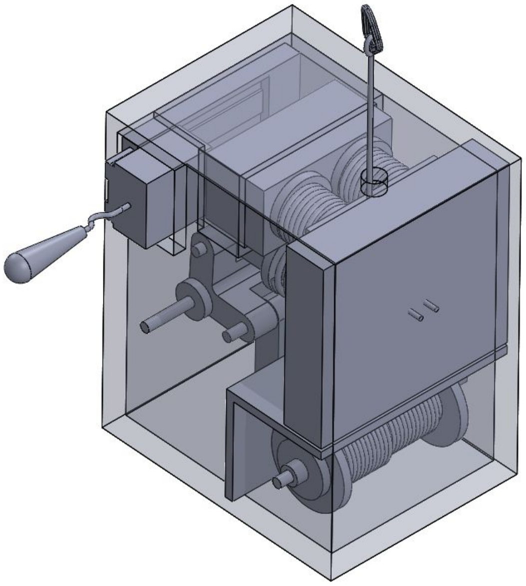


Figure 35. Isometric view of the CAD model of braking system

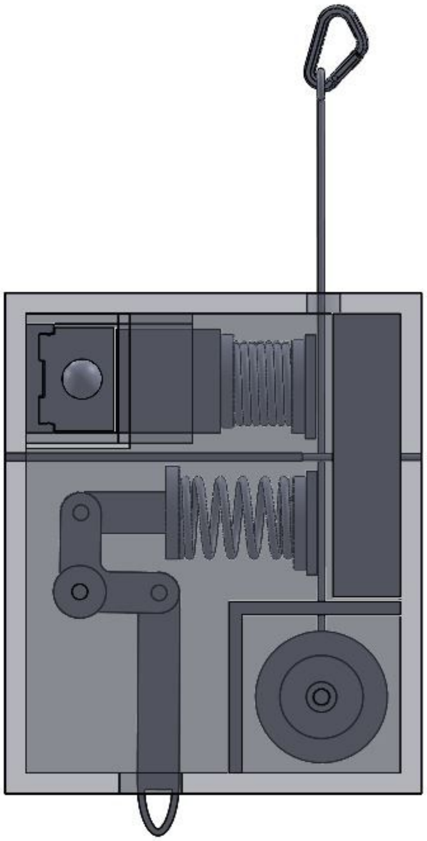


Figure 36. Front view of the CAD model of braking system

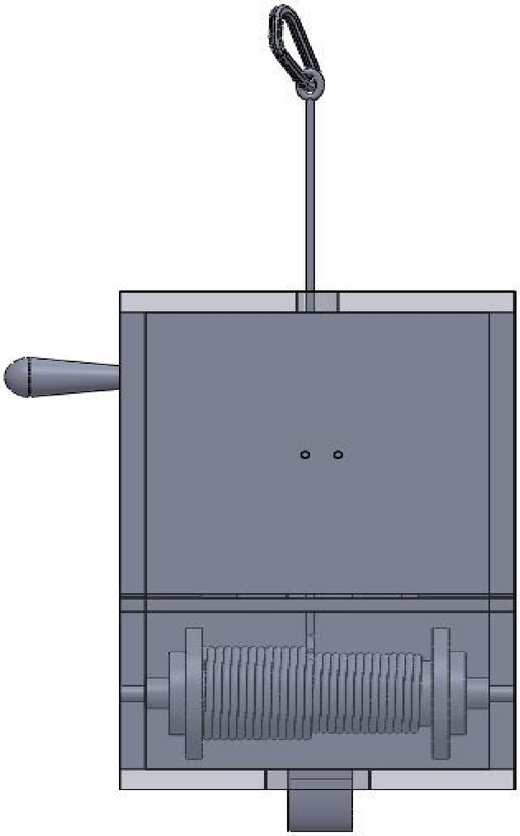


Figure 37. Right view of the CAD model of braking system

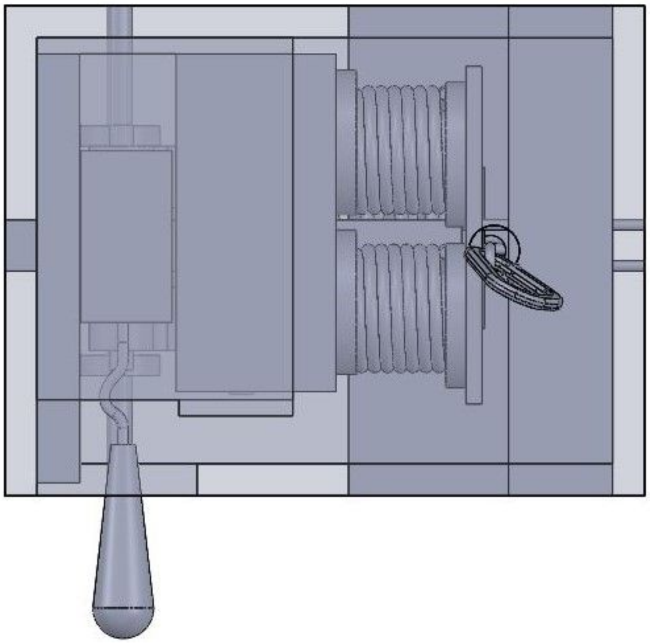


Figure 38. Top view of the CAD model of braking system

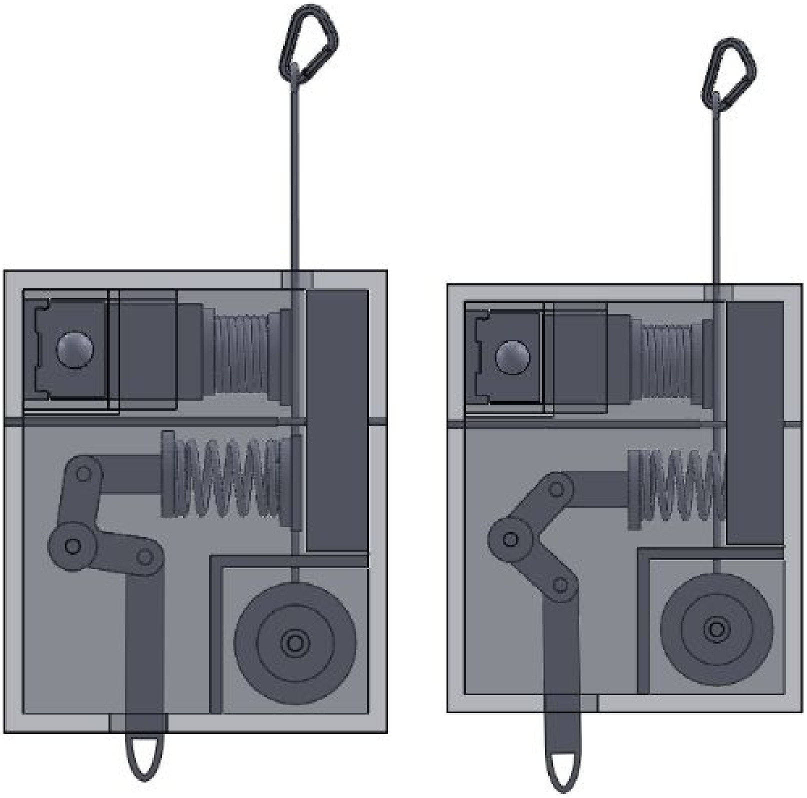


Figure 39. Snapshot of no weight applied vs. weight applied to the braking system

The figure above shows the state of the system after the user is hanging. The spring connected to the bell crank gets compressed and the user can easily pull out the brake handle to deactivate the hard brake. Since there is a coating applied to the rope, it will allow the system to move and once the coating is spooled out, the system will reach equilibrium again, but now it will be moving at a constant speed.

Plans for Manufacturing

Many of the parts in this project can be purchased. Some of them will need to be modified to perform certain functions per our design. However, other components need to be customly made or machined. Among these parts, the bell crank lever is the most critical. It needs to be made with tight tolerances as the friction on the rope depends largely on the travel of the lever. Another important part that needs to be machined is the housing. The housing serves not only as an enclosure but also as a structural frame that many parts rely on to operate.

The design of the lever is going to be evaluated in Solidworks Simulation to ensure it meets our design requirement. Once the design is confirmed, we will purchase an aluminum stock that is big enough for the lever to be made out of. The Computer Aided Manufacturing feature will be used to generate G codes for the CNC machine to perform different operations, for example, contour, pocket and drilling.

The parts that require machining are going to be manufactured using the CNC milling machine. We can use the CNC machine at Grove School of Engineering to machine the lever and other parts. Now this simply means that the rest of the parts can be either purchased or fabricated in our house to minimize the cost. The housing could be made out of metal to provide structural integrity. Therefore, we might need to weld the housing together.

We need to consider using lightweight and high strength material like aluminum to achieve as much portability as possible. However, certain parts may need to be made out of steel depending on the analysis on the strength requirement. For example, the pins that connect the lever and the arms as well as the hinge may be required to be made out of steel.

Our estimated build time is 8 weeks. The components in the active braking system, modification of purchased parts and the housing will take 2 weeks each. We will use another two weeks as back up to fine tune or trouble shoot other unanticipated problems that arise during the final stage of the assembly.

There will be very little to no cost on the labor of machining the parts. One of our team members is a machine shop technician and has access to CNC machines as well as welding machines in our school. Below is a cost estimation for the parts required for our system.

Cost Estimation of the built design

Product Name	**Product Cost**	**Manufacturing?**	**Purchasing?**
Lever	$94.65	Yes	No
Pins for lever	$27.74	No	Yes
3 springs	3 x $28.49 = $85.47	No	Yes
Brake pads	$50	No	Yes
Rope and Spool	$39.00	No	Yes
SpeedClock App	$1.99	No	Yes
Harness	$86.90	No	Yes
Carabiners (2)	$0	No	Yes
Hook	$4.30	No	Yes
Coating	$12.57	No	Yes
Spring Cups	$20	Yes	No
Rail	$60	Yes	No
TOTAL COST:	**$482.62**		

Table 6. Overall estimated cost for manufacturing

The total building estimate for the product is $482.62 which is below the limit of funding we will receive from the Grove of School of Engineering. However, it should be noted that this is an over-estimate; we will be working on reducing the cost and weight of this overall system. Although this is an overestimate, we are still below our maximum funding limit.

Plans for Testing

Because safety is the number one priority in this project, testing will play a vital role before the product can be delivered to the public for use. Testing for this project will be broken down into components. Below is a testing plan for the components in the braking system:

a) Lever and Spring Testing

After manufacturing the lever and assembling it to the spring, we will pull the arm of the lever attached to the user to see if the spring actually gets compressed. Once we are seeing a displacement that compresses the spring, then we will move on to testing different weights on the lever. Even though we have conducted an FEM study on the lever, we still want to make sure that the lever will not fail under various loads in a real-life situation.

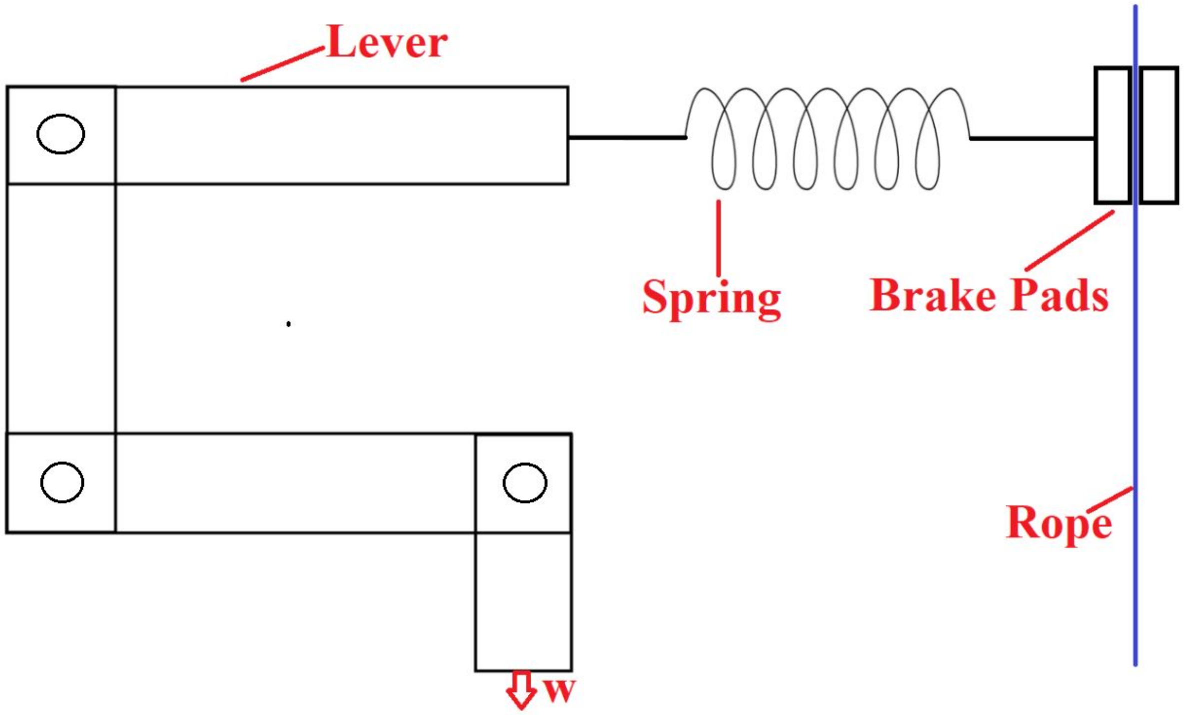


Figure 40. The set up for testing the lever and spring

As can be seen from **Figure 40**, we will be increasing the weight, W, on the bottom arm of the lever. Our weight increments will be: 50 lbs, 100 lbs, 150 lbs, 200 lbs and 250 lbs. We will conduct these tests in the cellar of the Grove School of Engineering building by asking Louis Hernandez for permission and supervision. One of the key pieces we will really be looking at is whether or not the lever fails. Additionally, we will be noticing how much the spring displaces. Because we do not want the spring to reach its solid length, we will simply record the spring's displacement using a caliper. We can easily borrow calipers from engineering clubs in the school building. This testing will not cost us anything because this testing can be done at CCNY. It will take about two days to do this testing where one day goes for planning on how to do the test, and to gather the supplies needed to conduct the test, and ask for permission to book a place to conduct the test. The second day will be devoted to actually doing the testing. Below is a table that we will fill out during this test.

Weight (lbs)	**Did the lever fail?**	**Spring Displacement(mm)**	**Reached solid length?**
50			
100			
150			
200			
250			

Table 7. This table will be used for lever and spring testing

b) Hardbrake Testing

Hard brake testing is a crucial step because it is the only system that ensures the system is initially stationary, allowing the user's weight to be registered to the system before descent begins. For safety concerns, we have to make sure that the hard brake works and does not let the user fall at the moment they get out of the building. Therefore, we will conduct the following tests to ensure that the hard brake system performs well.

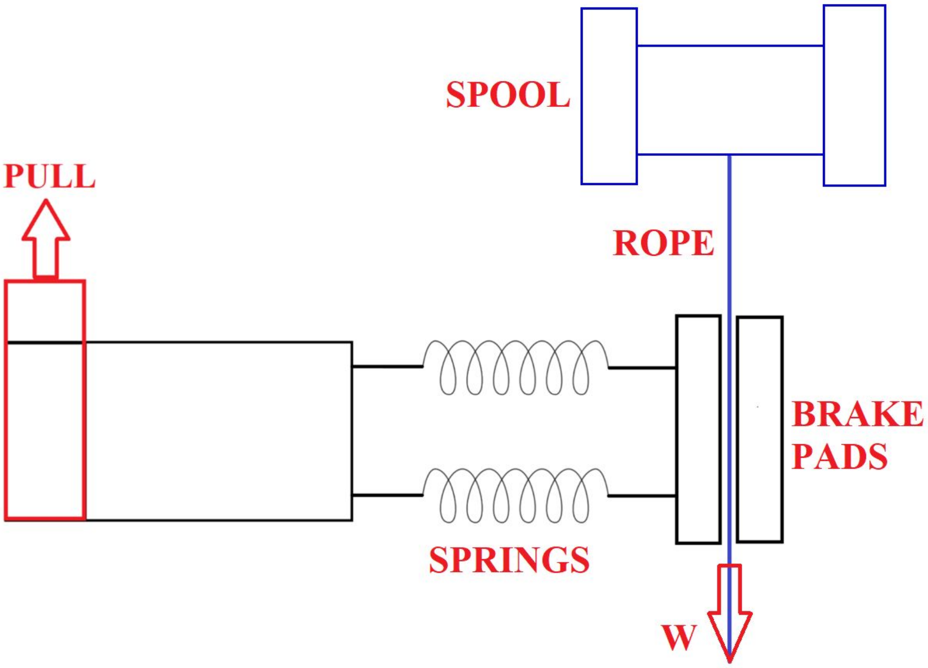


Figure 41. Drawing of the hard brake testing demonstration

As we can see from the figure, we will be testing for different weights, W, while the hard brake system is activated. We will manually compress the spring about 2 inches to create an approximate 500 lbs of normal force on the brake pads and lock it with the "red block" shown in the figure. One thing we will measure is how much the spring displaces; we want to make sure the spring does not reach solid length. Ultimately, what we are trying to test here is will the rope slide when we apply different amounts of weight to the rope? This is what the real-life scenario will look like; the user will be hanging and we want to make sure that the hard brake prevents the rope from sliding. However, different users will have different weights. Therefore, we will attach 50 lbs, 100 lbs, 150 lbs, 200 lbs and 250 lbs to observe if the rope slides or not. Below is a table we will fill out during the test.

Weight (lbs)	Does the weight descend or stay stationary?	Was it easy to pull the block to deactivate the hard brake?
50		
100		
150		
200		
250		

Table 8. This table will be used during the hard brake system testing

Similar to the lever and spring testing, this test should not cost us anything because after we have manufactured the components of the hard brake system, we can again perform tests in the cellar of the Grove School of Engineering building by asking Luis Hernandez for permission. The total time for this test will be two days where one day is devoted for planning the testing and the second day devoted for actual testing.

c) Pre-installed Hook and Rope Testing

Another important test required for this system is making sure the pre-installed hook does not fail under various loads. The first thing we will do is screw the hook onto a wall. After this is done, we will attach our rope to the hook and hang various weights to see if the hook comes out of the wall. In this scenario, failure is the hook totally coming out of the wall. Therefore, we will test the hook under 50 lbs, 100 lbs, 150 lbs, 200 lbs and 250 lbs. This testing should not cost us anything because we will be testing in the school building again by first asking Louis Hernandez for permission. The total time for this testing will be only one day because we simply need a place to hook and test various loads. We can use the same loads that we used in previous tests. Below is a table we will fill out while conducting this test. One important thing to note is that we are buying the hook that is able to withstand a load of about 1000 lbs. However, we still need to test the hook for redundancy. This test also takes care of the rope test because the weight will be attached to the rope that we will be using in the product.

Weight (lbs)	**Did the hook fail?**	**Did the rope fail?**
50		
100		
150		
200		
250		

Table 9. Table to be filled out for pre-installed hook and rope testing

d) Rope and Lubricant/Coating Testing

After the hard brake handle has been pulled by the user and the hard brake system is deactivated, the lever brake is still activated. Theoretically, the lever brake still should be able to keep the user at rest. However, this is not something we want. We want to descend the user to 3 ft/s. Therefore, we will be using either a lubricant or a coating on the nylon rope that reduces the coefficient of friction between the brake pads and nylon rope. In order to determine how much rope should be lubricated or coated, we need to perform certains tests. At this point in testing, we only need the lever, lever's spring and brake pads set up. To start our test, we will initiate by lubricating or coating the rope and see whether the rope starts to slide while the lever is pulled by weight. This test does not depend on the weight of the user, therefore, we will attach about 100 lbs to the lever's bottom arm. One thing we are looking at is whether the rope starts to slide or not. If the rope does slide, the next question is how fast does the weight descend? Recall, we need to keep a constant speed of 3 ft/s for the weight. Therefore, once the weight has reached 3 ft/s, the coating/lubrication needs to end and the brake pads need to slide against a normal nylon rope. Theoretically, this should work but it all depends on testing.

Once we know that the rope can slide with a lubricant on it, we will start to track the speed of the weight using the SpeedClock-Video Radar app. This app costs $1.99 on the app store. We will be lubricating the rope depending on the tests. For example, let us assume that with 1 feet of lubricated rope, the block was able to move at 1 ft/s, we will need to lubricate greater length of the rope. We will incrementally test what length rope works best to reach a speed of 3 ft/s. As of right now, we cannot make a table that we can fill out during testing because we do not know what rope length we will be coating initially. This test will cost us $1.99 and should not take more than two days. One day will go out for planning and asking for permission and one day goes for conducting the actual test.

e) Final product testing

This test is the final test for this product. After conducting previous tests and if those tests provide safe results, we will assemble the parts together and test the finalized product in real-life. However, for an initial test, we cannot have a human fall from a height and expect this system to work properly. There is a major safety concern with this: the human can possibly die. Even though we cannot test the device with a human at first, we can always test it with some object that weighs between 50 lbs - 250 lbs. However, even with this, there are major safety concerns. For example, if we are to do a test from the roof of the Grove School of Engineering building and this system does not work, there could be a great danger to the public walking on the streets. They could possibly get hit with a very heavy object at free fall rate. Therefore, it is best for us to not test this object from the roof but start from a lower height. For example, we will run the tests by stories of a building. We will first test the product from 1st story to the 10th story of a building. Because this test is height dependent, we will keep a constant weight of 250 lbs for all heights. The first story of a building is approximately 10 feet, therefore, we can conduct the first set of tests in the Grove School of Engineering building. However, we will need proper supervision and permission from Luis Hernandez. After the first set of tests, we will move on to higher heights. The total time for this testing will be about two weeks. First week will be for planning on how to conduct this test, where to conduct the test and if it is permissible by the school to conduct the test. The second week will be completely dedicated to testing and analyzing the results from the test. Below is a table that we will fill out while conducting this test. The most important parameter we are looking for is the speed of descent. In order to track the speed of the system, we will use an app called “SpeedClock - Video Radar”. This app is available for $1.99.

Height (Building Stories)	Object's Speed (ft/s)
1st	
2nd	
3rd	
4th	
5th	
6th	
7th	
8th	
9th	
10th	

Table 10. Table to be filled out for final testing

Another important factor that we will be looking at is how much heat is being built up in the housing due to friction. Because the rope is sliding on the surface of the brake pads, we expect lots of heat to be developed in the housing. However, because we already have two openings; one at the brake handle and one where the user hooks to the braking system, we believe this will be enough to ventilate the whole braking system. In a worst case scenario, a user of 250 lbs weight will be descending from a 10-story building (approximately 100 feet). Because the friction will be equal to the user's weight for constant descent speed, we can use physics to calculate how much heat will develop.

$$Q_{developed} = F_{friction} * displacement$$

$$Q_{developed} = F_{friction} * displacement = 250\ lbs\ * 100\,feet\ = 25000\ lbs * feet\ = 33895.449\ Joules$$

Since most of the components in the system are made of aluminum and are able to withstand high temperatures, we are not concerned. However, we are concerned about the brake pads burning out because there is a constant brake being applied by the user. Depending on how our tests go, we will decide whether we need to add more ventilation to the system. If the brake pads are not affected poorly by a constant brake then we do not need to think of a better ventilation system.

This will be the conclusion of our testing. The total time for all the tests is about two weeks. If there are problems with our tests, testing can last up to a month but according to our plans, it should take about two weeks only.

The project website can be reached at:
https://amizuka000.github.io/fireescape/design-process.html

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