# Optimizing Climbing Cam Design

A Major Qualifying Project

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# Abstract

The goal of this project is to create a better mechanical design for micro cams, small camming device used in rock climbing, to increase their holding power and safety. As a result of researching ways to create a better micro cam, our team designed a micro cam which was manufactured and tested against international standards. Although the results did not meet the standards required, the micro cam showed promise that signifies the design can be iterated on in the future.

# Acknowledgements

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# 1 Introduction

Humans have always been explorers. From the summit of Mt Everest to the cliffs of Yosemite National Park, the limits of human ability are constantly getting rewritten. Rock climbing is one of the many endeavors in which human limits are tested.

Individuals who climb (who will be referenced as “climbers” throughout this document) scale rock faces using only their hands and feet. Climbers often grip small ledges and features in the rock with their fingertips that can be as small as only a few millimeters. A combination of incredible strength and proper athletic form keeps the climber from falling off the rock and being defeated by gravity. The ways in which a climber uses their body to climb varies with the type of rock climbing being performed. The most popular type of rock climbing is free climbing, in which climbers ascend the rock using only their body for upward movement with no outside forces helping them. There are 3 primary different types of free climbing: Bouldering, Sport Climbing, and Traditional (simply known by most climbers as “Trad” and will be referenced as such throughout this document) climbing. Each of these types of free climbing come with their own unique challenges. Bouldering consists of short, very challenging routes that are climbed without a rope for protection and are often no more than 20 feet off the ground. Sport Climbers climb routes that can be more than 30m tall. On sport climbing routes, climbers attach themselves, using their rope, into bolts, a form of protection, that are predrilled into the wall as they ascend. If the climber were to fall, the rope fought become taught against the bolts and prevent the climber from hitting the ground. Trad climbers climb similar routes to sport climbers with the difference being that they must bring protection with them when they climb. In climbing, protection is gear that is placed by the climber into the rock that the climber will then trust in the event of a fall.

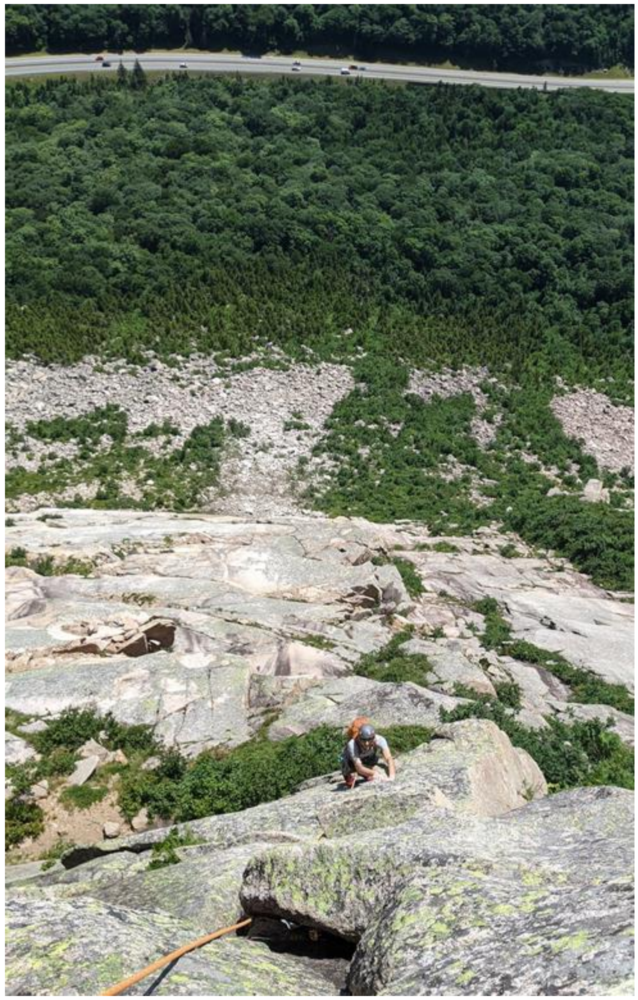


Figure 1: A climber ascends Cannon Cliff in New Hampshire

When climbing on both sport or trad routes, the climber is protected from falling by a belayer and a rope system that hoists up the climber when the rope is in tension, as seen below in Figure 2. This system uses a rope to catch the climber in the event of a fall. To do this, a second climber is needed. That second climber is known as the belayer and is responsible for catching a climber's fall with the rope. In Figure 2 below, the belayer is the women with the blue helmet. She is belaying by using a device, known as the climbing community as a belay device, to prevent the rope from creating more slack, which will prevent the climber from falling. The belay device locks the rope in place by increasing the friction on a singular point of the rope. The climber, shown as the man with the yellow helmet in the figure below, climbs the wall and places protection in the rock. The climber then places the rope through a carabiner on the cam so that in the event of a fall he will be caught by it and not hit the ground.

Figure 2: a Belayer (left) belays a climber (right) with a rope (Pink) who has placed a cam in the rock; Courtesy. (2017, August 7). *Keep the rope organized and distractions minimized. Tether the belayer (piece shown in front for clarity)* [Photograph]. Https://www.climbing.com/skills/learn-this-protect-your-belay-protect-your-belayer/.

Sport and trad climbing differ in the type of protection used. In sport climbing, bolts that carabiners are placed to into are installed into the rock. In trad climbing, the protection the climber can place varies depending on the type of rock, but the most common type of removable protection is a spring-loaded camming device, simply known as a cam in the rock climbing community. A cam is a device that is designed to be placed in a crack in the rock where it then expands to fill the crack and catch the climber in the event of a fall by exerting a force outward on the walls of the crack.

The widespread access that commercial climbing gyms brought to the sport has caused a massive increase in the popularity of rock climbing. In their annual report published in 2019, The Outdoor Industry Association indicated that in 2018 there was a 1.70% increase in the number of individuals participating in indoor climbing from the previous year (Outdoor Foundation, 2019). The explosive growth rate of new climbers may make it more likely for accidents to occur as those climbers' transition to harder and more dangerous aspects of the sport, such as trad climbing. As climbing grows it is important to find ways to make the sport safer to protect newer climbers.

The American Alpine Club publishes a yearly report titled *Accidents in North American Climbin*g that documents climbing related injury and accident reports that occurred in the previous calendar year in North America. The report draws from all types of climbing, including different climbing-related sports such as ice climbing. In the 2019 edition of *Accidents in North American Climbing*, the $10^{th}$ leading cause of accidents was gear failure, specifically cams (American Alpine Club, 2019). This may not appear to be a high priority problem to solve, but when zooming into specifically trad climbing it can be observed that working to improve the cam is an important endeavor.

In September of 2020, popular climbing magazine *Rock and Ice* worked to compile data from the past 30 years of *Accidents in North American Climbing* and break that data up by the individual types of climbing (Caroom, 2020). This is important because the different types of climbing are practically different sports and have different rates and types of injuries. Over the past 30 years, the data shows that 48% of all trad-related climbing accidents are because of inadequately placed protection or from protection pulling out of the rock. When the data is explored further, it shows that the 3% of climbing injuries is not representative of the bigger issue that is specifically to trad climbing.

An example of these devices failing occurred in April of 2016 when a climber started up a climb in South Lake Tahoe (MacDonald, n.d.). On that climb, he placed 4 micro cams into the rock wall. A micro cam is the smallest version of a cam, and thus has the highest risk of failure when placed. The climber fell after climbing 25 feet up the route, ripping out his first, third, and fourth cam. This resulted in a ground fall. This accident is one example of micro cams failing. Fortunately, this climber survived the fall, but other climbers have not been so lucky. As climbing becomes more popular, more people are going to be using cams. These devices must be made safer so that more people can climb without risk of injury or death.

## 1.1 Stakeholders

When it comes to improving the safety of climbing cams there are many stake holders involved. The most obvious is the recreational climbers, however search and rescue teams, regulatory agencies, and retailers all must be taken into consideration. Recreational climbers, People practicing the traditional style of climbing, frequently use cams as their preferred form of protection. Most of the time, when a climbing takes a fall when trad climbing a cam is the only thing that stands between a safe fall and impacting the ground, which could result in injury or even death. Increased safety comes with lower rates of injury and more trust by the climbers in their gear. If the climber, the consumer, is one side of the coin, cam-manufacturers would be the other. A safer product would lead to a larger captive market for cam-manufacturers, such as Black Diamond or Wild Country, along with the potential for fewer lawsuits.

Sometimes people in the outdoors, not just climbers, make risky decisions. Sometimes these decisions can put people in perilous place where they are in need of rescue. An often-overlooked benefactor for improved cam safety would be search and rescue teams. According to the Interior National Park Service's Technical Rescue Handbook, search and rescue teams in locations where climbing rescues may occur keep cams in their arsenal (Phillips, 2014). The added protection against a fall protects both the search and rescue team and the climber being rescued. In this scenario, the search and rescue team would need to, most likely, repel down the rocky face to reach the individual in danger. Once there, they would need to be able to get the person out of danger. The cams they use would need to be able to withstand the stresses of the rescuer, the individual in danger, and the abundance of gear the rescuer must bring with them. The more reliable the cams are, the smoother and more stress free the search and rescue operation can be.

In addition to these tow stakeholders, it is important to consider how the regulatory agencies and retailers will respond to these new cams. Based on past cam innovation by Totem we can infer that there will be little friction in the testing of the cams. Additionally, if a retailer adopted totem cams, we can assume that they will support a cam with similar feature that has been certified by the regulatory agencies.

## 1.2 Rock Climbing as a Sport

Recreational climbing dates back to the late 1800s, but its explosion in popularity is much more recent. Recreational climbing started outside in the mountains of Europe, specifically the Dolomites of Italy (Wilkinson, 2019). At the time, climbers used any means necessary to ascend the treacherous faces, this meant driving tools like pitons, small steel spikes that act as an anchor for the climber, into the rock to pull themselves up when their physical strength failed to be adequate. Over time, this was met with criticism largely due to the tools wearing down the rock and leaving visible damage. It wasn't until the 1970's when major strides were made in creating gear that would preserve the natural beauty and climb-ability of the crags, the climbing term for a place where people go to climb outdoors. From this era, the style of traditional climbing was born and removable gear such as nuts and cams came into being.

The commercialization of indoor climbing gyms has introduced newer generations to the sport. According to the Climbing Business Journal, "the commercial climbing industry grew at a rate of 6.9 percent in 2016, 10 percent in 2017, and 11.8 percent in 2018" (Olhorst, 2020). These surges in revenue in the climbing industry mean that the average skill level of climbers is decreasing as new people join the sport. Because of this, the levels of safety that gear such as cams provide are of significant importance as these new climbers gain an interest in outdoor climbing, specifically traditional climbing which is something a gym cannot provide the experience for.

## 1.3 Locations and Types of Rock

Climbing is a sport that can be found in a variety of places across the globe. From the granite cliffs of New Hampshire to the sandstone of Southeast Germany to the resin climbing holds at the local indoor facility, climbing takes many forms. In regard to traditional climbing and outdoor climbing in general, not all rock is the same. Different types of rock provide different climbing experiences (Eberhardt, 2016). One of the primary types of rock preferred by climbers is granite. Granite is perfect for traditional climbing. The hardness of granite allows it to accumulate in large formations such as mountains and cliffs. When erosion does occur due to the elements, it most commonly does so vertically. This creates features that are exceptionally good for placing gear such as cams that hold strong in the cracks of the course rock. The preference of crack climbers, sandstone is another popular type of rock. Sandstone is not nearly as hard as granite and erodes very easily. Due to this, sandstone rock typically contains incredible crack climbing where a single crack splits down the face of the rock and the climber must use techniques such as hand jams to carefully scale the stone. Another type of sedimentary rock that is popular among climbers is limestone. Limestone is created as the result of the remains of organic structures such as coral being compressed over the course of millions of years. Limestone is extremely hard and resistant to erosion, making it perfect for forming immense overhanging features. While it is typically less ideal for traditional climbing, it is the ultimate surface for sport climbing.

# 2 Background

A Spring-Loaded Camming Device, commonly known as a cam, is a device that is placed into a crack in the rock. This cam then expands when loaded by a fall. This expansion arrests the climbers' fall. After the climber has loaded the cam, it can then be removed by a second climber, who acted as the belayer during the first climber's ascent, who climbs up after the leader while the first climber, now at the top of the climbable section of rock, belays. This device is used in a form of climbing known as traditional climbing. Traditional climbing is a style of climbing where the ethic is that all equipment used to arrest a climber's fall is removable from the rock. This is opposed to sport climbing where bolts are permanently drilled into the rock. This ethic is also known as clean climbing because no gear is left behind. This style is the predominant style of climbing on bigger mountains and big walls.


Figure 3: a well-placed cam in a granite crack; Recreational Equipment, Inc. (n.d.). A properly placed cam. Lead Climbing: How to Place Trad Gear. Recreational Equipment, Inc. https://www.rei.com/learn/expert-advice/place-trad-gear.html.

## 2.1 Parts of a Cam

While some manufacturers create cams with slightly different designs, there are some components that are universal among all cams. Starting from the bottom of the cam, all cams possess a stem. The stem, which can be seen below in Figure 4, is the part of the cam that would protrude from the crack in the rock (Metolius Climbing, n.d.). This part is typically flexible and ends in a thumb loop that makes the cam easier to handle and place in the rock. The thumb loop is also where the sling would go. The sling is made from a tough piece of material that ultimately connects the cam to a carabiner, which then hold the rope. Additionally, the stem houses the trigger, which is used in the placement of the cam. When the trigger is pulled, the lobes of the cam retract and make the profile of the cam smaller. This allows the climber to place the cam inside a crack that is smaller than the lobe's profile when fully expanded. Once the cam is in the crack, the climber would release the trigger and the device would be cammed inside the crack. If the cam would need to be removed, the climber would once again pull the trigger to release the tension so the cam can be easily removed. At the head of the cam is the axle. The axle runs through the top of the cam stem and houses the cam lobes. Typically, a cam has three or four cam lobes. Springs span between the lobes and the axle. These springs constantly attempt to spin the lobes about the axle so that the lobes are in the fully expanded position, creating constant tension against the interior of a crack.

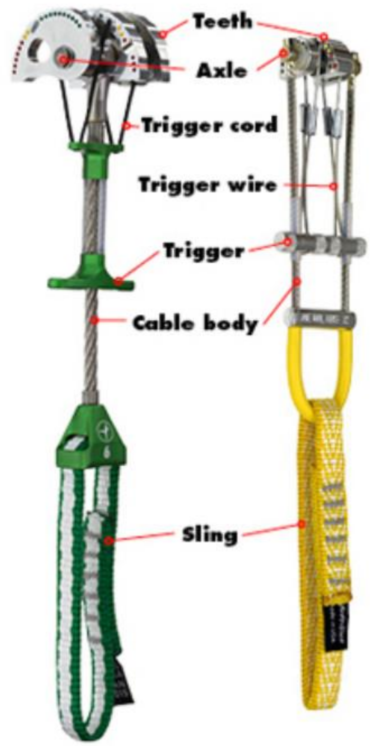



Figure 4: Parts of a climbing cam; Metolius Climbing. (n.d.). Cam Care: Metolius Climbing. Cam Care | Metolius Climbing. https://www.metoliusclimbing.com/cam-care-and-maintenance.html.

## 2.2 Friction

Friction is the resistance to motion during sliding or rolling that is experienced when one solid body moves tangentially over another with which it is in contact. The resistive tangential force, which acts in a direction directly opposite to the direction of motion, is called the friction force (Halling, 1978). The friction force is the most important to climbers. It is what keeps them on the wall and the protection, such as a camming device, in place. The laws that govern friction are credited to the works of Charles Augustin Coulomb, a French engineer in 1773 (Popova & Popov, 2015) who confirmed Amontons theory, which will be explained in the next section, and developed the two-term friction formula we know today.

### 2.2.1 Amontons Theory

If two solid bodies are loaded together and a tangential force is applied to one of the bodies, the value of the force required to move the body initially is the static friction force. Once the static friction force is overcome by the tangential force, the tangential force must now only overcome the kinetic friction force, which is less than the static friction force. Figure 5, shown below, shows this difference by demonstrating how the static friction coefficient is higher than the kinetic friction coefficient. In Figure 5, a constant tangential force is applied over time. As the static friction force becomes unable to match the tangential force, it gives way to the kinetic friction force. These two different forces are what make up friction (Halling, 1978).

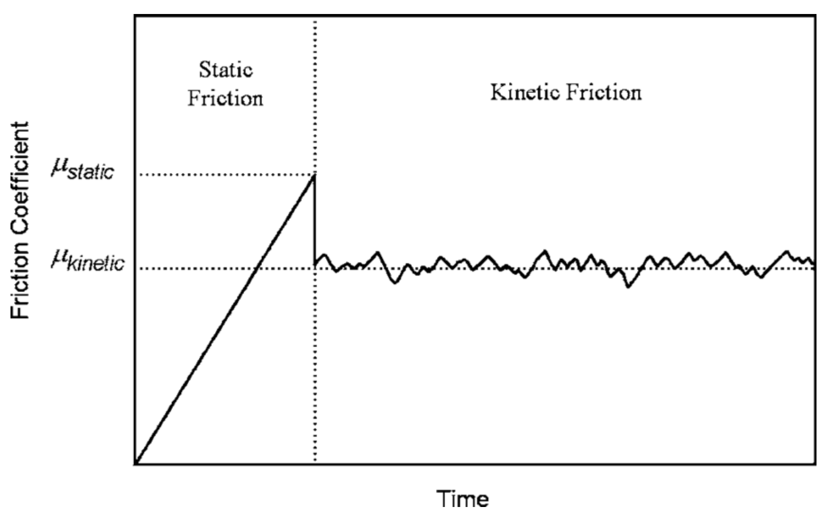



Figure 5: Comparison of the static and kinetic friction coefficients when a constant, linear force is applied over time; Polycarpou, A. A. (2007). Schematic of a typical friction coefficient showing static and kinetic friction. Static Friction Experiments and Verification of an Improved Elastic-Plastic Model Including Roughness Effects. ResearchGate. https://www.researchgate.net/figure/Schematic-of-a-typical-friction-coefficient-showing-static-and-kinetic-friction_fig2_228362816.

### 2.2.2 Static Friction

Static friction is a systematic response governed by two the laws of friction, known as Amontons' Laws. The first law states that friction force is directly proportional to the normal load. This normal load is the tangential force. The proportionality constant μ is known as the coefficient of friction, shown below in Equation 1. The coefficient of friction varies for the same material based on where the system is in kinetic friction ($\mu_k$) or static friction ($\mu_s$). The coefficient of friction is determined through experimentation. (University of Washington, n.d.)

$$F = \mu N \qquad (1)$$

The second law of friction states that the friction coefficient is independent of the apparent area of contact between the two bodies in the system. In the second law it is important to examine the difference between apparent contact area and real contact area. Apparent contact area is how the surface contact appears to the human eye. Real contact area considers the roughness and asperities of the surface at the micro-surface level. Two pieces of metal may appear to be perfectly flat at first glance, but at the micro-surface level the two materials have unique surface roughness. This explains why Amontons first rule of friction does not account for apparent surface area (Akchurin, 2016).

To account for real surface area, it is important to look at the equation that under pins most friction theories, shown below in Equation 2. In Equation 2, F is the friction force, s is the constant force per unit area, and A is the real contact area. This formula allows the relationship between normal force and real area of contact. Assuming that the contact between the two surfaces is plastic, or the two surface fit together to create a perfect bond, the real area of contact is directly proportional to the normal force. This is the reasoning behind the first law of friction neglecting surface area (Braun, 2018).

$$F = As \qquad (2)$$

It is also convenient to express this rule in terms of a friction angle θ defined as:

$$\mu_s = tan\ (\theta) \qquad (3)$$

This equation defines the angle at which a body of any weight placed on a large incline at less than θ from the horizontal will remain stationary, if the angle is increased to θ the body will slide down. This is critical for cam design because this is also known as the camming angle (University of Washington, n.d.).

### 2.2.3 Dynamic Friction

As opposed to static friction, dynamic friction occurs when two objects are in motion and sliding against each other. Dynamic friction has the coefficient $\mu_k$ and is not as large as the static coefficient between two materials, except in some cases (Meriam & Kraige, 2002). Same as the static friction force, the friction force after sliding starts between two objects is the coefficient of dynamic friction multiplied by the normal force, $F_{Dynamic} = \mu_k \cdot F_N$. Dynamic friction is typically dominated by surface roughness and contact area (Persson, 2013). In the case of rock climbing cams, dynamic friction may occur during the fall's impact on the cam in the rock. The cam may slide a small amount against the rock wall due to the impact angle, or it may completely slide out of the crack if improperly placed or loaded. Typically, there should not be much dynamic friction, if at all any. The only dynamic friction that would sometimes occur if the cam were properly placed is the head torquing because the angle of impact is not directly in line with the cam.

## 2.3 The Physics of Camming Devices

When thinking about camming devices, there are two ways that they can be modeled: rigid and elastic (Custer, n.d.). The rigid model demonstrates the physics of the cam under the assumption that the materials will not be subject to deformation. The elastic model adds the elements of shear and material deformation for a more accurate model.

### 2.3.1 The Rigid Cam Model

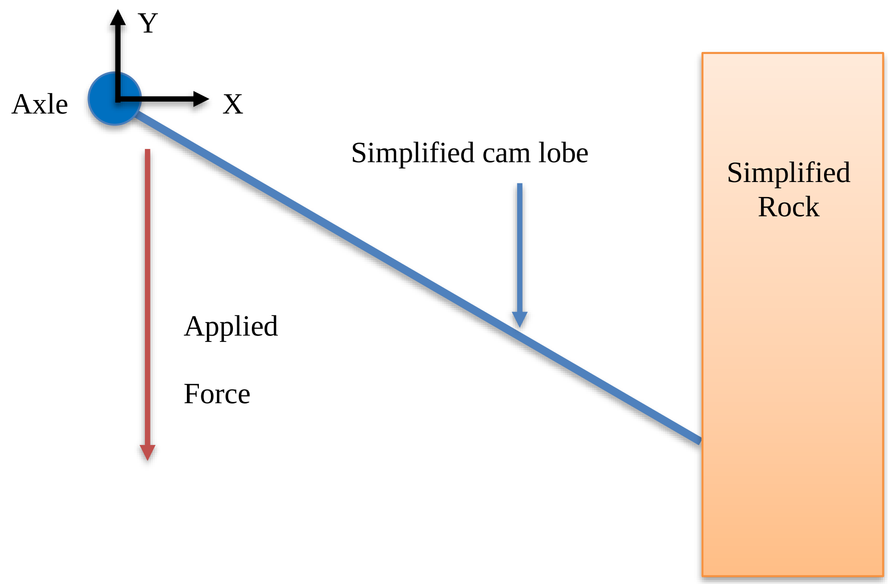



Figure 6: A basic camming model demonstrated by a single simplified cam lobe. The cam lobe can be approximated by a line as the line is a ridged model of the cam. On one side it is attached to the axle with a pin joint and on the other it is constrained by the wall

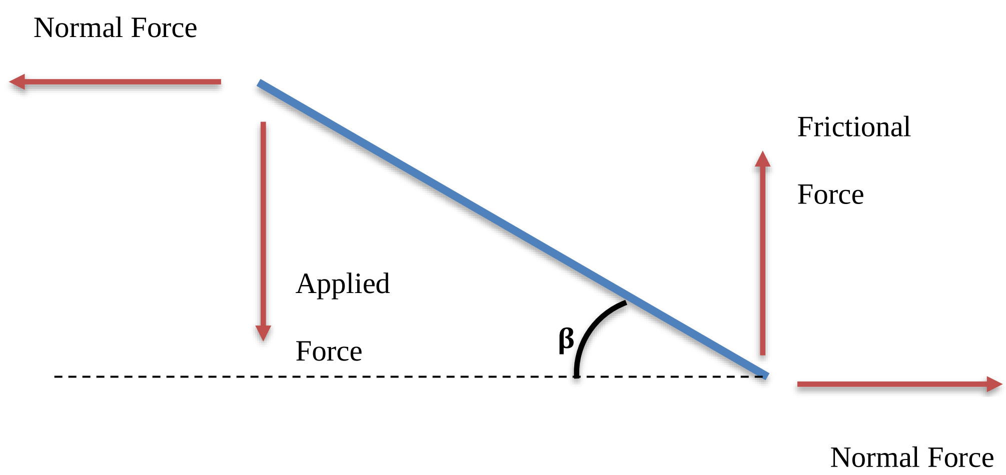



Figure 7: Free Body Diagram of a basic camming model with a single lobe

The rigid model for a camming device is not as accurate as the elastic model but does serve as an informative introduction to how camming devices work (Custer, n.d.). In its most basic form, a camming device can be represented as a rod placed diagonally in between a parallel crack, as shown in Figure 6 in a study done by the Massachusetts Institute of Technology (which can be abbreviated as MIT). In Figure 6, it can be observed that as a force is applied to the rod at one end, normal forces of the rod act perpendicular to the crack. As long as the rod is wedged in place, then applying more force to the system will result in higher normal forces acting on the crack. On the opposite end of the rod, acting in the opposite direction of the applied force is the frictional force. When looking at Figure 7, it can be observed that the frictional force only exists on one side of the rod. This is because the side of the rod the applied force is active would be where the axle of the camming device would be located, which exhibits negligible friction. If the vectorial sum of these four forces is equal to zero, then the camming device will remain wedged in the crack. From this, two important equations can be derived. The first important equation is shown below as Equation 4. This equation demonstrates the relationship between the applied force and the normal force applied by the camming device to the crack. In this equation, which is also seen in Figure 6, **β** is the angle the device makes with the horizontal plane, shown above in Figure 7. This angle is more commonly known as the camming angle. The applied force must be equal to the normal force multiplied by the tangent of the camming angle to stay cammed in the crack. This can be simplified by stating the coefficient of friction must also be greater than the tangent of the camming angle, shown below in Equation 5.

$$F_{applied} = (F_{normal}) * (tan(\beta)) \qquad (4)$$

$$\mu \geq tan(\beta) \qquad (5)$$

If combined with the previous equation, this means that the applied force divided by the normal force must also be less than or equal to the coefficient of friction. The coefficient of friction is also calculated as frictional force divided by normal force. When this fact is combined with the previous two equations, the result Equation 6, which is shown below. This proves the importance that friction plays in a camming device, as to stay cammed in the crack, the frictional force must be greater or equal to the applied force (Custer, n.d.).

$$\frac{F_{applied}}{F_{Normal}} \leq \frac{F_{Friction}}{F_{Normal}} \qquad (6)$$

To best utilize the friction between the camming device and the crack, a simple rod will not do, not when the lives of climbers are on the line. To achieve this, a shape must be used that would maintain a constant angle with the surface of the crack (Custer, n.d.), shown below in Equation 7. In this equation, R is the radius of the camming device at any given point, $R_0$ is an arbitrary constant, θ is the angle from the x-axis, and tan(**β**) is the camming angle. This is the equation for a logarithmic spiral. With the lobes of the camming device in this shape, as the applied force increases, so do the normal and frictional forces, along with the radius of the camming device (Custer, n.d.).

$$R = R_0 e^{\theta} * tan(\beta) (7)$$

### 2.3.2 The Elastic Cam Model

In reality, a camming device is not indestructible. It is susceptible to deformation and material failure, which is why the elastic model is a more accurate representation of the capabilities of a camming device. The three properties of the camming device that are included in the elastic model that were not present in the rigid model are Young's Modulus, Poisson's Ratio, and the shear yield stress.

When subject to an applied force, the point on the lobe of the camming device that is contacting the surface of the crack will deform (Custer, n.d.). An example of this deformation can be observed in Figure 8, shown below. While in the rigid model the area of contact would be a singular point, in the elastic model the deformation causes an area of the camming device's lobe to be contacting the crack.

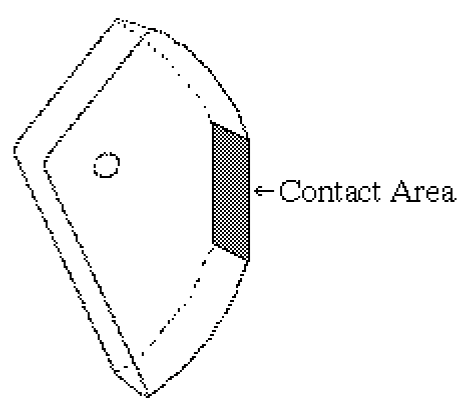



Figure 8: The deformation of a cam lobe upon contacting a surface; Custer, D. (n.d.). An elastic model of the holding power of spring loaded Camming devices used as rock climbing anchors (1176367887 881441435 S. Ruff, Ed.). Retrieved February 02, 2021, from http://web.mit.edu/custer/www/rocking/cams/cams.body.html

This contact area can be calculated using Hertz's Theory, as seen below as Equation 8. Although, it should be noted that this equation, while more accurate than the elastic model, is only an approximation as it does not account for a few factors (Custer, n.d.). This is because Hertz's Theory is designed for cylinders. In this case, the curve of the logarithmic spiral is approximated as that of a circle to fit the role of the cylinder in the equation. Additionally, the equation does not account for the holes in the cam lobe (created to reduce weight) and the potential for a ribbed contact surface for better grip. It also does not include the applied force, nor the effects of plastic deformation.

In Hertz's Theory, represented as Equation 8 below, the deformation of the cam is taken into consideration (Custer, n.d.). In this equation, R is the radius at the point of contact with the crack, W is the width of the camming device's lobe, P is the contact pressure, and E is the cam lobe material's modulus of elasticity. Against the surface of the rock, the cam lobe will warp, even if just by a small amount, under the pressure and the amount in which it warps is determined by the cam lobe's size and material, along with the forces and pressures acting upon it from the rock. The deformation of the cam lobe can affect how the force from the cam lobe is distributed on the rock.

$$A_{contact} = 2\sqrt{\frac{((4*F_{normal})*(1-P^2)*(R*W))}{\pi E}} \qquad (8)$$

### 2.3.3 Non-Parallel Cracks

All of the previously provided physics of how a camming device operates do rely on one factor to be accurate: the crack must be parallel in nature. In reality, not all cracks where a climber would place gear will be that perfect. Some cracks are non-parallel, or flared (Totem MT, n.d.). A flared crack gets narrower the deeper it goes into the rock, creating an angle with the camming device, as shown below in Figure 4. This angle changes the reaction force experienced by the camming device. In a parallel crack, the angle β is 0. When β is zero, it is negligible from the system. In a flared crack, the angle β becomes greater than zero. When calculating the reaction force of the wall of the crack on the camming device, β must be subtracted from the camming angle, shown as α in Figure 9.

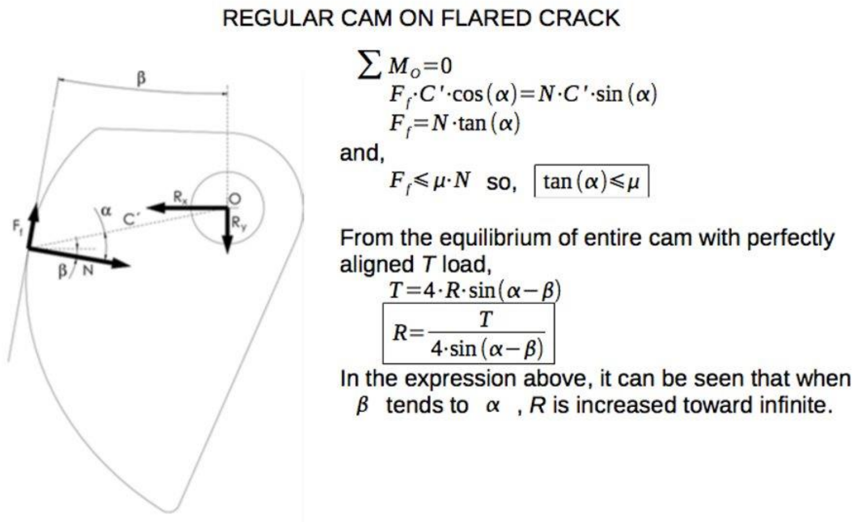



Figure 9: The physics of a cam in a flared (non-parallel) crack; Totem MT. (n.d.). TotemCam Mechanical Principles. Basque County; Totem MT.

### 2.3.4 Fall Factors

The applied force that the camming device experiences is determined by a variety of factors. Primarily, these factors are the climber's weight, the weight of the belayer, and the fall length. The more mass the climber and belayer have, the larger the impact force will be on the cam in a fall, regardless of the length of the fall. This falling distance can be categorized using fall factors (Petzl, 2021). The fall factor is a number, typically between zero and one, that represents the percentage of the distance the climber fell relative to how far the climber is from the belayer. For example, as shown in Figure 10, the climber is seven meters above the belayer and falls a distance of two meters. Two meters is (approximately) 30% of 7 meters, so the fall factor is 0.3. Fall factor does not account for the stretching of the rope.

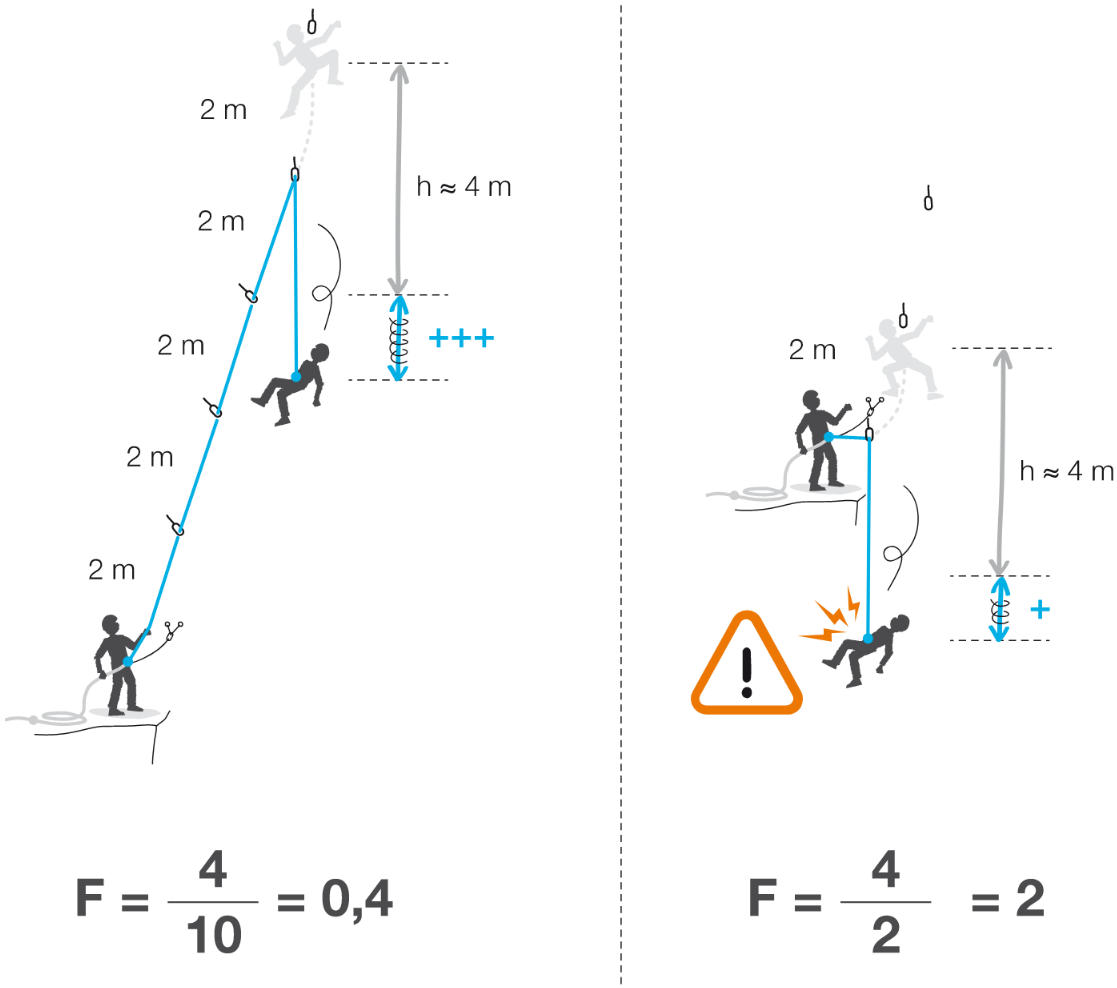



Figure 10: A demonstration of how fall factors are determined; Petzel. (n.d.). Fall factor and impact force - theory. Fall factor and impact force - theory - Petzl USA. https://www.petzl.com/US/en/Sport/Fall-factor-and-impact-force---theory?ActivityName=rock-climbing.

Figure 10 demonstrates a theoretical total length of the rope. In reality, many climbing routes will not have the rope run in that perfect of a straight line. As the rope runs through the carabiners suspended from the wall, it can create sharp angles, as seen below in Figure 11. Due to these sharp angles, the force of the fall is on a singular point that is closer to the climber due to the increased friction between the rope and the carabiner (Petzl, 2021). This reduces the effective rope length. Due to this, the relative relationship between the fall distance and the rope length is significantly higher, and the higher the fall factor, the more force the protection in the fall, be it carabiners or a camming device, experiences.


Figure 11: A demonstration of how fall factors are determined in a non-linear belay; Petzel. (n.d.). Fall factor and impact force - theory. Fall factor and impact force - theory - Petzl USA. https://www.petzl.com/US/en/Sport/Fall-factor-and-impact-force---theory?ActivityName=rock-climbing.

### 2.3.5 Testing Applied Force

The applied force on a piece of climbing gear is typically determined by taking falls at different fall factors with climbers and belayers of various weights. To test this, the climber would be hanging onto the wall at the appropriate distance to satisfy the fall factor (Petzl, 2021). The carabiner that the climber is directly above would have a scale attached to it. When the climber lets go of the wall and falls, the scale will be pulled downward and measure the impact force. While this is typically done on a sport climbing set-up, it is an effective and efficient way of measuring the force of the fall as it would be the same on a traditional climbing fall.

## 2.4 Failure Modes of Cams

Rock climbing has a relatively small injury rate compared to many other physical sports, contributing only 10% of all mountain-related accidents (Rauch, Wallner, Ströhle, Cappello, & Maeder, 2019). When using a spring-loaded camming device for climbing, there is always going to be a small chance of the cam failing. The failures are usually due to a lack of knowledge of the climber and not using the cam properly. Cams are designed to be safe under large impact forces so that they do not slip out when a climber misses a hold and falls. Most micro-cams can withstand 5kN of force, which is enough to pull a car up the wall. As the size of the width of the camming head increases, so does the strength of the cam until a certain point.

### 2.4.1 Failure Due to Poor Placement of Cam

The most common cause of climbing related cam failure is due to lack of knowledge and poor placement of the cam. Cams are designed to take a downwards impact force. If the force is at an angle and not pulling directly away from the frontal lobes, then the cam will not be able to withhold as much force as it is certified for. Proper downward placement of the cam, as shown below in Figure 12, is extremely important due to these forces (VDiff, n.d.).

Figure 12: Example of properly placed cam; VDiff. (n.d.a). [Cam walking out of place]. Retrieved February 09, 2021, from https://www.vdiffclimbing.com/cam/

Another part of setting a cam that often causes failure is overcamming and undercamming (Black Diamond Equipment, 2019). When placing a cam, it is important to make sure that the frontal lobes of the head are at least slightly activated and also not over-activated. The proper camming angles of the frontal lobes are shown below in Figure 13 to demonstrate both overcamming (in the yellow) and undercamming (in the red). Undercamming is the more dangerous of the two and can usually cause the cam to slip out of the crack. Overcamming usually will generally not result in a cam failure, however, it causes the cam to be more difficult to take out of the crack.

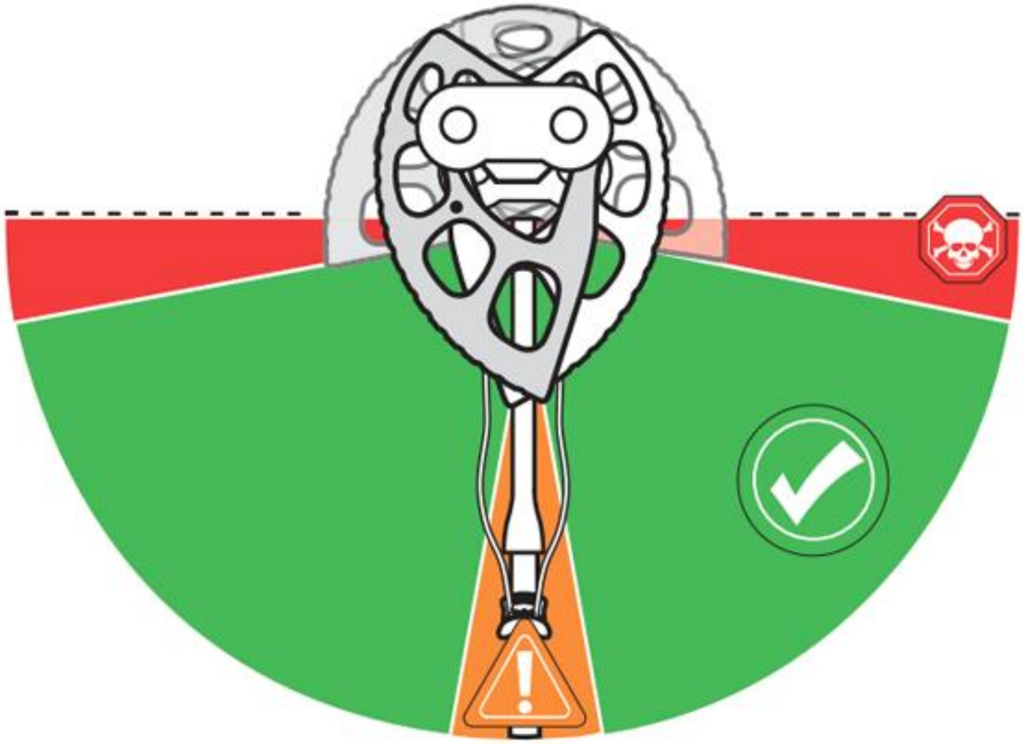


Figure 13: Example of overcamming and undercamming; Black Diamond Equipment, Ltd. (2019). Product Instructions - Camalot™ C4 & Camalot Ultralight [PDF]. Salt Lake City: Black Diamond Equipment, Ltd.

### 2.4.2 Failure caused by weather

Another possible cause of cams failing is due to poor weather conditions. Weather conditions can sometimes be unavoidable, but it is possible to plan and check the weather before a rock-climbing trip. Rain can cause the risk of rock climbing to increase. In the rain, it is more difficult to set proper placing cams, easier to slip off of holds and fall onto the cams, and the water increases the likelihood of a cam slipping out of the crack due to a loss of friction.

### 2.4.3 Failure due to poor rock quality and lack of friction

Before climbing, it is often required to check the rock quality to ensure safety when climbing. Some examples of poor rock quality are sandstone, limestone etc. These rocks are a mix of soft and easy to pulverize and smooth rocks that does not allow the cam to catch. Other situations that can cause a loss of friction are when there is lichen, ice, dirt, or moss on the rock that can work as a lubricant against the cam. These lubricants are common in cracks that are rarely climbed or in alpine environments. The lubricants allow the cam to slide out of the crack when loaded and are a common source of injury.

### 2.4.4 Failure due to walking of the cam

When placing a cam in a flared crack, there is a risk of the lobes "walking" out of place (VDiff, n.d.). This movement is caused by the rope shaking the cam head as the climber goes up the wall. As shown below in Figure 14, the small movements will move the head to be tilted into an angle and make the cam either impossible to retrieve or wiggle out of position. When the cam wiggles out of position it could look well placed, however, when loaded the cam could fail.

Figure 14: Example of cam “walking” out of place; VDiff. (n.d.a). [Cam walking out of place]. Retrieved February 09, 2021, from https://www.vdiffclimbing.com/cam/

### 2.4.5 Brittle fracture failure

A less common cause of cam failure is brittle fracture of the cam brought by material defect or inclusion. As shown in the below in Figure 15, this can cause the frontal lobes of the cam to suddenly snap when taking an impact force (Dirtme 2007) Since this failure mode is so uncommon, it is speculated that the defect could be brought about during the manufacturing process and not be picked up later on during the inspection process. Any micro-crack in the part could propagate with more use of the cam. A small bump on the lobes could also create a stress concentration point, thus leading to high levels of stress and a likelihood of snapping.

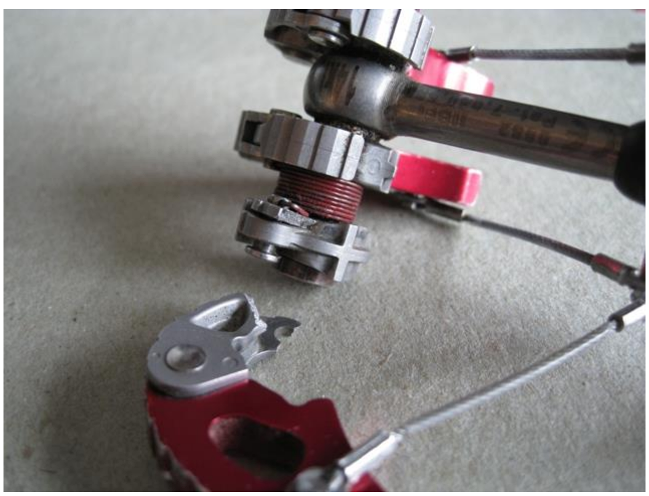


Figure 15: Example of brittle fracture in a cam; Dirtme (username). (2007). A cam that has broken due to brittle fracture. Omega Cam Breaking! rockclimbing.com. https://rockclimbing.com/cgi-bin/forum/gforum.cgi?do=post_view_flat;post=1733591;page=1;sb=post_latest_reply;so=ASC;mh=25.

### 2.4.6 Head torque failure

The cause of head torque failure is when the angle of the force being applied on the cam is not directly in the opposite direction of the head. This could be due to either the cam being improperly placed, or the fall being too unpredictable and impacting the cam at an odd angle. If the fall is not in the same direction as the placement of the cam, the force will then impact the head at an angle. The angle will force the cam in a spinning motion, thus either torquing the cam out of the crack or bending the frontal lobes as shown below. If a bend like this happens, the cam will usually fall out of placement. Figure 16 below shows an example of what happens to a cam during a head torque failure (Anderson, 2013).

Figure 16: Example of bent frontal lobes of a cam; Anderson, A. (Director). (August 16, 2013). Cam failure in climbing fall [Video file]. Retrieved February 9, 2021, from https://www.youtube.com/watch?v=DHjNxgbAhQM. Image taken from time 0:53

## 2.5 Fractals

In researching how to improve the holding power of a cam lobe through the use of a surface coating, fractals became a topic of discussion. Prior studies have shown that application of fractals onto a surface may have the ability to increase the friction between that surface and other materials. Fractals are a branch of study of both mathematics and art that creates endless patterns that repeat forever (Patrzalek, n.d.). The patterns created by fractals are typically identical to the whole, but at a smaller scale. When zooming in further, the pattern repeats itself again. The shape and frequency of these fractals can be determined by their fractal dimension, which is traditionally a value between 1 and 2. The closer the fractal dimension is to 2, the more frequent and intense the fractals are. In mathematics, there are two traditional ways of modeling fractals, being the Mandelbrot Set (seen below in Figure 17) and the Julia Set. In regard to engineering, the applications of fractals and the effect that it has on the friction of materials is a fairly new area of study. There is not a lot of research that has been done on the topic, and even some opposing evidence, but the general research that has been conducted appears promising.

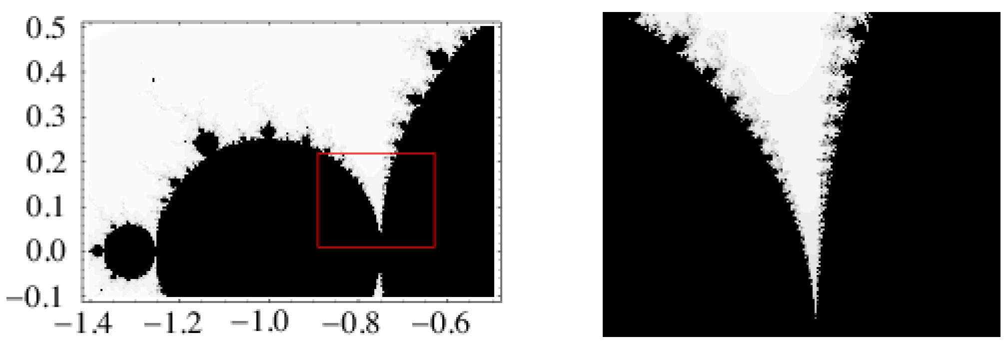



Figure 17: Example of a Mandelbrot Set; Weisstein, E. W. (n.d.). Sea horse valley Mandelbrot set. Mandelbrot Set. https://mathworld.wolfram.com/MandelbrotSet.html.

In a study done by D. A. H. Hanaor, Y. Gan, and I. Einav with the University of Sydney in Australia, the effect of fractals on friction was explored on aluminum surfaces (Hanaor, Gan, & Einav, 2013). This is important because cam lobes are traditionally machined out of aluminum. The researchers created aluminum disks, dimensioned to by 25mm in diameter and 3mm thick, and pelted them with glass beads. These beads were extremely small, measuring only 250-300 micrometers in size. This gave the aluminum disks a surface roughness by creating a quasi-random fractal surface on them. The disks were then subjected to applied stresses measuring between 20 and 203 megapascals. These stresses warped the fractal surface, changing aspects of it such as the amplitude, or the physical height, of the fractals. These surfaces were scanned and given fractal dimensions between 1 and 2. Both before and after the creation of the fractal surface, the friction of the aluminum disks was tested on quartz substrate.

The results of this experiment determined that the surface roughness, fractal amplitude, and the fractal dimension decreased the more compressive stress the fractal surface experienced. The results of the experiments showed that the coefficient of static friction did increase the higher the fractal dimension was. The increase in the coefficient of static friction was incredibly minute and the impact made by the presence of the fractals on the surface quickly became negligible due to the fractal amplitude decreasing as force was applied to the surface (Hanaor, Gan, & Einav, 2013).

# 3 Project Approach

## 3.1 Client statement

Micro cams have a small margin of safety. This is a common cause of accidents in traditional climbing. In April 2016, a climber started up a 5.10b finger crack at Pie Shop, a granite crag near South Lake Tahoe, California (MacDonald, D., n.d.). His first four pieces were all micro cams, and when he fell about 25 feet up, the first, third and fourth cams ripped out, resulting in a ground fall. This was just one of several instances of micro-cams failing in falls, many of which are documented in "*Accidents in North American Climbing*". While climber error may be a contributing factor, we believe there is a design solution to improve the safety of these devices.

## 3.2 Goal Statement and Objectives

The goal of this project is to increase the safety of micro cams by determining common mechanical failure modes and designing a new cam to address these failure modes while maintaining a competitive price. In the interest of increasing safety of micro cams, we outlined the following research objectives:

- **Objective 1:** Determine common mechanical failure modes of micro cams
- **Objective 2:** Design solutions to address these failure modes
- **Objective 3:** Test these design solutions utilizing industry standards for cams
- **Objective 4:** Evaluate, implement, and give recommendations on the best solution for improving the safety of micro-cams

## 3.3 Market Needs

Before exploring how the problems that plague micro cams can be solved, it is important to first determine what such a cam would need to be competitive and sought after in its niche market. The factors that would make an improved micro cam competitive vary in nature, some revolve around the improved cam being similar enough to other cams on the market to be familiar and intuitive to use, but different enough to have to stand out amongst the rest.

Starting with the familiar before venturing into territory that would set the cam apart from its competitors, the cam must be of a competitive weight and price. Climbers must haul numerous cams up the rock faces when they climb, so having the improved cam be of a comparable or less weight to other cams of the same size without giving up safety is important. If the improved cam weighs significantly more than others on the market, the consumer might look elsewhere as they would not want the added weight on their harness to impact their climbing performance. In regard to the price, cams tend to already be fairly expensive products, especially when one takes into consideration the number of cams a traditional climber is likely to purchase over their lifetime. If the engineering required to improve the safety and reliability of the micro cam creates a product that costs substantially more than its competitors, then the cam is much less likely to be purchased by consumers. While the goal is to improve safety, it cannot come at the cost of drastically increasing the cost of the product.

Continuing with the needs of the improved micro cam being similar to what is currently available, the user interface must be similar to other cams on the market. Almost all cams that are commercially available have a similar structure when it comes to how it is used, in regard to the stem and trigger. This is because it is likely that a climber will have multiple brands of cam on their person when climbing and if every cam had a different mechanism for pulling the trigger to engage the cam, the likelihood of misplacing a cam increases, and in turn the chance of injury. Keeping a similar user interface will make the cam safer and make it more appealing to consumers, as it will already be something they are comfortable with.

The stem of the cam must also be flexible, just as the stems of most cams currently available are. This is because not every crack in the rocks being climbed is the same, so a flexible stem allows for the cam to be placed in more situations than it would be able to if it was rigid.

Moving away from the similarities and into the realm of what can be improved to set the improved micro cam apart from its competition, consumers are always looking for cams that are reliable on all types of rock. Some types of rock are better than others as they are more sound and of a higher quality. Cam manufacturers are always looking to improve the performance of their cam in lesser-quality rock, and the design of the improved micro cam is no exception. The improved micro cam must be able to perform well, and even better than the competitors, on low-quality rock such as sandstone.

In addition to this, the improved micro cam must have a larger margin for error than other cams on the market. Due to the small size of the micro cam and the equally small size of the cracks they are trying to be placed in, it is harder to place micro cams correctly compared to larger sized cams. Cams placed incorrectly tend to walk out of place and into less ideal positions within the crack and in some cases pop out of the crack. In order to advertise the improved micro cam as safer than its competitors it must be easier to place.

When a micro cam is placed correctly, the improved micro cam must be more reliable than its competitors. A consumer expects that when they correctly place a micro cam that it will be reliable in the case of a fall. Material failure in cams is rare, but disastrous when it occurs. The improved micro cam must be stronger than its competitors and more resistant to material failure.

The last major market need is for the improved micro cam to be able to enact single-sided loading. Although some currently available cams are capable of this, the majority, especially in the realm of micro cams, are not. The ability for a cam to engage in single-sided loading drastically increases the safety as in the event of walking out of an ideal placement or placing a cam in a crack where not all the lobes are capable of being engaged, the cam will still be able to hold the majority of its rated load. This decreases the risk of injury. Since micro cams are difficult to place perfectly, the improved micro cam is likely to attract the attention of consumers with this safety feature and outcompete other cams on the market.

## 3.4 Functional Requirements

With the market needs established, the next step is to determine what functions the improved micro cam must possess to meet those market needs. Starting simply, the market needs that deal with the similarities between the improved micro cam and the other micro cams available on the market have straightforward functional requirements. In order to have a competitive weight, the improved micro cam needs to be made of lightweight and strong material so that the improved micro cam's weight is comparable to other top brands while being at least as strong. The functional requirement for the comparable price is that the cost of the cam compared to others on the market, both to produce and to sell, must be minimized without compromising the strength or reliability of the cam. The stem of the final product must also be made of a flexible, yet strong, material to fit into angled cracks and inconvenient environments. It also must have a similar user interface to current cams so that climbers previously using other cams are comfortable and familiar with how to properly use the improved micro cam.

In regard to the innovative market needs, the improved micro cam should apply a higher frictional force on the crack than the competitive set so that the cams walk less than the competitive set. Even if the cam is imperfectly placed, an increased frictional force between the cam and the crack will increase the holding power of the improved micro cam. Building off this, the improved micro cam should be able to maximize the force of the fall to increase holding power so that cams pull out less increasing safety. As the force pulling down on the cam increases, so does the force of the cam against the crack. The higher that force against the crack is, the stronger the holding power of the cam will be. If the cam is imperfectly placed, the cam needs to resist walking when experiencing an impact force. If the cam walks less, then the chance of it popping out of the crack is greatly decreased, increasing the safety of the system. Cam lobs should distribute the load in the crack such that the load transmitted to the rock is less at a singular point.

If the load is distributed along a larger surface area, the chance of material failure will be lessened and improve the safety of a properly placed cam. Additionally, the larger surface area of the contact between the cam lobes and the crack will increase the frictional force and holding power. Regarding the market need of needing single-sided loading, when the cam is placed in a single sided loading scenario, the cam should hold half of the rated load. This is superior to most cams currently on the market, giving this cam commercial appeal, and would greatly decrease the chance of failure in the event of walking or moving within the crack.

## 3.5 Design Requirements

In order to bring the concepts in the functional requirements into reality, the improved micro cam will need to be designed in a way that successfully incorporates these concepts. Many of the designs we have formulated work together to fulfill multiple market needs and functional requirements at once. Starting with the similarities between the improved micro cam and the other competitors on the market, the comparable weight and cost need to be considered in the design process. No matter the final design, these to market needs come down to one main factor: manufacturing the cam using the appropriate material. We need to engineer the micro cam with a material that is lightweight and cost-effective, yet still strong enough to be reliable in the face of taking upwards of 5kN of force. The flexibility of the stem of the cam relies on these factors as well, along with the need to research or design a cable that is of an appropriate material, yet flexible enough to allow the cam to be placed in angled cracks and inconvenient environments. Regarding the need for the user interface to be similar to other cams currently on the market, we would need to design a trigger mechanism that can fit and operate along the flexible stem yet mimic the feel of trigger mechanisms found on other cams.

When it comes to the improved micro cam's performance on low quality rock, we will design the cam with the width of the lobe in mind. A wider cam lobe means increasing the surface area between the lobe and the crack, and when the rock quality is poor and prone to breakage the increased frictional force may help keep the cam secure in the face of adversity.

The innovative market needs require innovative designs in order to successfully function. A major area of the cam design we explored was the incorporation of a cable-based moment in the cam lobe. As the force pulling down on the cam increases, such as a climber falling, the cams will engage as standard, per other cams on the market, but in addition a cable running along the lobe will also become engaged and get taught. As the cable pulls on the lobe, the moment it creates about the axle of the cam will increase the force the cam is exerting on the crack. This cable moment system has been explored by other cam manufactures, but never in a micro cam due to its size. In addition to this, we explored the idea of the lobe having a coating or the ends of the lobe being made of an alternate material, such as an extremely hard rubber. The rubber or rubber-like surface will allow for the cam lobe to deform a minute amount and form a closer bond with the interior of the crack, in turn increasing the holding power of the cam.

## 3.6 Constraints

While the functional and design requirements are based on the market needs, something that was created through the eyes of what consumers look for in a cam, there does exist a set of requirements that all cam manufactures must have their cams meet in order to be sold commercially. This set of standards is set forth by the UIAA, also known as the International Climbing and Mountaineering Federation (International Climbing and Mountaineering Federation (UIAA), 2018). The standard for camming devices, titled “Frictional Anchors”, is standard UIAA-125 and EN-12276, which can be found in Appendix A.

When designing the improved micro cam, some important considerations based on the UIAA’s standards must be made. The UIAA states that a cam must be able to withstand at least 5kN (International Climbing and Mountaineering Federation (UIAA), 2018). Whatever the maximum load of the cam is, it must be marked on cam in kilonewtons. Additionally, when testing the cam only the strength needs to be evaluated, which would result in only performing a straight down tensile test of the cam inside a simulated crack made of metal. The standard states that the friction between the lobes and the crack does not need to be tested, although we do plan on testing for this regardless. The cam must also be tested in two positions: a large position and a small position. The large position is calculated by subtracting the cams minimum range from its maximum and multiplying it by ¾, then adding the minimum range. The small position is the same formula but multiplying by ¼ instead of ¾ when appropriate. Although, the standard states that if the difference between the maximum and minimum ranges is less than 5mm, then only one position needs to be tested. This single position is calculated the same as the previous two positions, with the only change being multiplying by ½ instead of ¼ or ¾ when appropriate.

# 4 Design Concepts

Once we identified the market needs, design needs, and constraints, our next task was determining possible design concepts that fit those requirements. Having already done extensive background research to build our designs off of, we brainstormed four basic design concepts to later evaluate.

## 4.1 Cable Moment Cam

To increases the frictional force between the cam lobe and the rock one must increase the normal force. A solution to do this is to exert a moment about the central axis the cam lobe is attached to. In this case we chose to use a cable to apply such a moment. A cable runs from the outer most edge of the cam lobe to the stem and down to the thumb loop [see Figure 18]. In this design the thumb loop is webbing material that covers the cable that is running from the lobs. This allows for single side loading as well as a common user interface. The advantage of this design is that it can effectively add a moment to the cam lobe while maintaining the narrow lobe size. The disadvantage of this design is that a thin cable or wire is needed to apply the moment and must withstand a 5kN load.

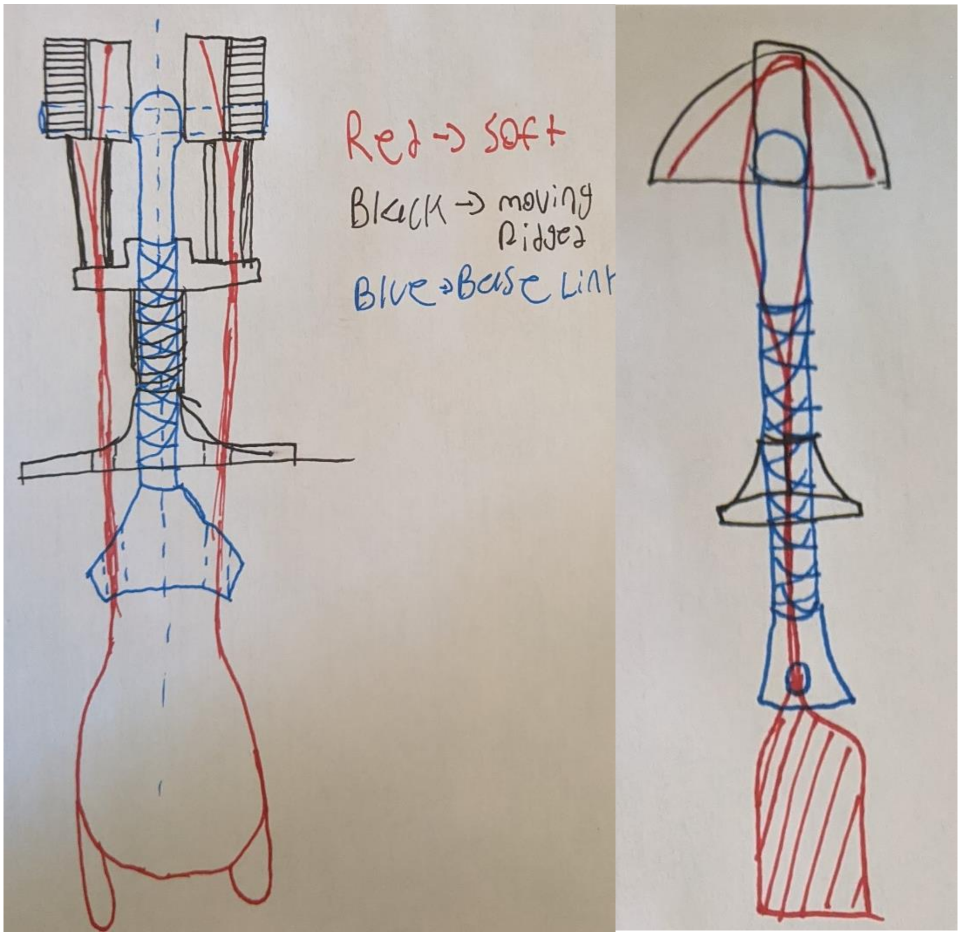



Figure 18: Conceptual drawing of the cable moment cam

## 4.2 Piston Cam

The piston cam design uses pistons to apply a force to the end of the cam lobe [see Figure 19]. Similarly, to the cable moment cam this design would increase the normal force between the cam lobe and the rock thus increasing the friction. the piston would have to attach to a mechanism on the central axis of the cam and rotate with the lobe. The primary challenge with this design is the geometric constraints that a micro cam provides. As the cams we are working with are micro cams the piston would have to have a diameter of less than 5mm and a length of 11mm. in order for the piston to be effective it would have to provide a large amount of force to the lobs and the pressure needed to do that in such a small space would be too great for most materials to hold. Additionally, to manufacture such piston we would need to use electrical discharge machining which is viable for a prototype but not for large scale production

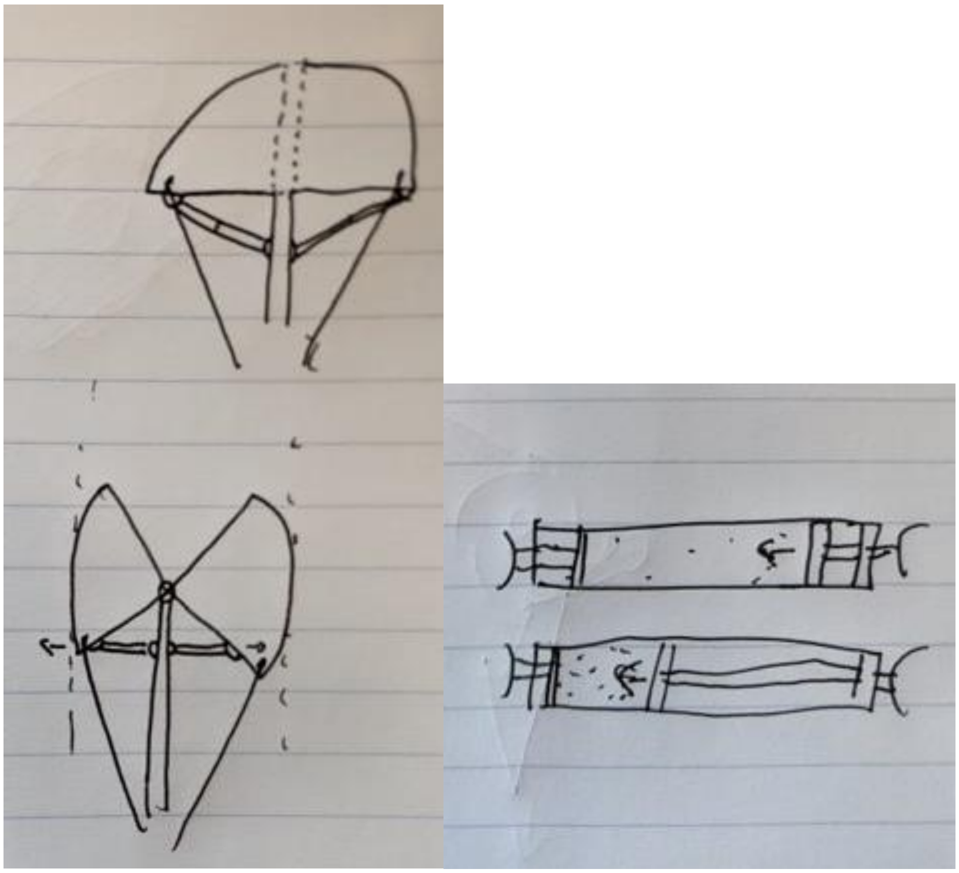


Figure 19: Left: side view of the piston cam concept, Right: Piston

## 4.3 Cleat Design

The cleat design is similar to a normal cam, however, in the center of the lobes there would be a rope tightly secure [see Figure 20]. This idea was based off a sailboat cleat, but almost the exact opposite. Instead of the cleats contracting on the central rope when pulled, the cleats would expand outwards on the crack. When the climber falls, this rope is pulled down and forces the lobes to expand outwards. This concept is somewhat similar to the cable design; however, it lacks in range. Since there would be a rope going down the center, there would need to also be a pin on either side to secure the lobes. This would greatly increase the width of the overall head of the cam while not increasing the overall range of which it can be used. This design would also be dependent on the strength of the rope and whether or not the cleat wears it down after repeated usage.

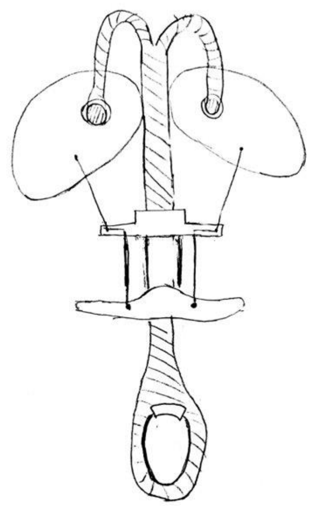


Figure 20: Cleat-cam concept drawing

## 4.4 Ratchet and Pawl Design

A concept looked at in the early stages of the design process was the ratchet and pawl mechanism. The idea behind this mechanism is that as the ratchet spins in one direction, the pawl moves over the round side of the teeth of the ratchet and allows it to spin freely, as shown in Figure 21. When the ratchet attempts to spin in the opposite direction, it can only move so far before the pawl catches on the blunt side of the teeth and stops the motion of the ratchet. This is because the pawl is being pulled towards the ratchet by the force of a spring or similar system. This spring is only strong enough to pull the pawl to the ratchet and can easily be pulled up. When the pawl is pulled up, it would free the ratchet to spin freely in either direction.

In terms of how the ratchet and pawl mechanism would be incorporated into a design of a micro cam, it would serve as a backup system if walking was to occur. The sketches below, Figure 21, illustrate a potential design of the mechanism within the micro cam. Each lobe of the cam would have its own ratchet and pawl mechanism. As the cam expands to push against the walls of a crack, the ratchet located on each lobe would spin freely with the pawl moving over the teeth of the ratchet. This would allow for the cam to freely expand without interruption, as any interruption would likely result in cam disengaging from the crack. Any attempt by the cam to reduce its range in the crack would be halted as the pawl locks against the blunt end of the teeth on the ratchet. Aside from the climber pulling the cam's trigger to release it, the cam would be unable to reduce in range, making sure it can only get more secure in the crack. When it is time to remove the cam from the crack, the trigger that reduces the cams range would also pull on the pawl and release it from the teeth of the ratchet so that the cam may be taken out of the crack.

Figure 21: Ratchet and Pawl Cam Design Concept

While the system does provide a level of backup security to the cam that previously did not exist, the engineering required to produce the product could outweigh the benefits. The system would have to be extremely small between the lobes of the micro cam without interfering with the interior of the crack that is the outermost section of the lobes. This would put an extraordinary amount of pressure on the part of the pawl that is contacting the ratchet in the event of a fall. Additionally, the advent of adding a ratchet and pawl system to each lobe would drastically increase the width of the micro cam. If the crack the micro cam is being placed in is shallow, the addition of the ratchet and pawl system might require some of the cam to not fit into the crack, making the overall system less safe.

# 5 Material Innovations

In addition to developing a unique mechanism we also will coat our cam lobe in a substance to increase the coefficient of friction between the cam and rock.

## 5.1 Adhesive Coating

One briefly contemplated design concept was to possibly try and apply a liquid to the edges of the cam that would solidify and stick to whatever material it is touching when impacted, similar to the tongue of a frog. This would allow the cam to stick when the climber's fall impacts the device and also be easy to slide in and out of the crack when the climbing is placing or taking the cam out. A major problem with this design is that it would stray very far into the field of chemical engineering, which is none of our expertise. Additionally, if this coating is sticky enough to increase the holding power of the cam in a crack, then it would be sticky enough to run the risk of collecting dirt and other particles. If this occurs, it may diminish the effectiveness of this design and increase the routine care required for the cam as it would need to constantly be washed in-between climbs. We are not truly sure if such a liquid coating is physically possible to create.

## 5.2 Fractals

The idea of etching fractals into the surface of the cam was explored. As stated in Section 2.5, the addition of fractals to a surface would increase the coefficient of friction that the surface has with other surfaces.  While this innovation seems promising at first glance and may yield positive results for a short time, the effort required to produce that short-term improvement may not be worth the time and cost. Fractal etching is typically done using silicon, not aluminum. There have not been many studies done using aluminum as the medium for fractal etching, with the most prominent study being the article used in Section 2.5 by D. A. H. Hanaor, Y. Gan, and I. Einav with the University of Sydney.

Based on their study, we do not have the equipment necessary for etching aluminum the way they had done it. Additionally, the amplitude of the fractals would quickly decrease under the force of the cam once the cam lobe surface is against that of the rock face. This decrease in amplitude would lead to a large reduction in the additional coefficient of friction that the fractals are providing. Even before the fractal's amplitude is diminished, the increase to the coefficient of friction that the fractals provide would be minute. Overall, while the addition of a fractal-etched surface to the cam design may lead to increases in the holding power, those increases would likely be so small that they are practically negligible and not worth the investment of getting the appropriate equipment required to create.

## 5.3 Nanowires

Camming devices use friction forces to arrest a climber's fall. However, there is a limit to the mechanical normal force that the cam can produce due to its geometry. In nature geckos can overcome this limit by using the Van der Waals force an example of this interaction is when a gecko walks up a flat wall. This adhesion interaction is between spatulae and a glass surface. Spatulae are hairs less than one micrometer in diameter. These spatulae generate a Van der Waals force of 0.4 micro newtons however there are approximately 14 million. All of these spatulae combined help hold the gecko to the wall. We hope to utilize a similar technology to increase the safety of small cams.

The Van der Waals force is an always present molecular force between two atoms. This force is caused by a dipole-to-dipole attraction. A dipole occurs in an atom when most of the elections in the electron cloud move to one region thus giving the atom a polarity that attracts a neighboring atom. These dipole-dipole forces not only occur within a molecule but also between two surfaces or a plane and a sphere. The equation that governs this force for an interaction is: $F = \frac{2}{3}\pi RW$Where R is the radius of the sphere and W is the van der Waals constant for surfaces (50-60 mj/m^2) (Leite et al., 2012).

To apply this technology to cam lobes the best way to do this would be through nano wires. Nano wires much like gecko spatula would create this Van der Waals force between the rock and the lobe. The best way to manufacture nano wires for our application would be to grow them in a bottom up.in this case a gold seeding approach would be best. For our application, the best method for getting nano wires would be to purchase them on a flexible substrate and adhere that substrate to a cam lob. Unfortunately, the cost of nano wires is high, as much as $500 a gram.

## 5.4 Rubber

Another possible material improvement that could be conducted in the future is applying a rubber like substance to the lobes of the of the cam. The idea behind this is that the rubber like substance would allow a larger area of surface contact from the wall to the cam lobe. This is due to the rubber allowing more elastic deformation on the lobes and increasing the surface area. The rubber could also possibly increase the coefficient of friction between the cam lobe and the wall. Overall, the idea behind the rubber would allow for the cam to walk less and allow for greater holding power with the cam placed in the crack. To apply this coating, we were possibly thinking of designing molds to dip the lobes into with the rubber being in a liquid form. After applying the rubber, we would allow it to dry and solidify onto the lobes.

# 6 Final Design

After conducting research on the science behind how climbing cams operate and determining different ways in which the holding power of a climbing cam can be increased. We decided on a final design to move forward with. This design would focus on a concept design that our research demonstrated has the most potential for accomplishing the goal of increasing the holding power of the cam.

## 6.1 Choosing the Final Design

After we completed researching the science behind how cams operate and brainstormed different designs that could potentially increase the holding power of micro cams. The next step in this process was to evaluate which proposed design has the most merit. To do this, we created a design matrix. A design matrix is a table that assigns an importance (as a value between 0 and 1) to different variables that have value to the cam. Examples of these are shown below in Table 1, being variables such as the range of the lobes and ease of manufacturability. The higher the number, the more important that variable is when considering the final cam design. Once the importance was assigned, the four design concepts we conceived were added to the table. The design concepts, like the importance, are assigned a number for each variable. This time, the value can range from 0 to 10. This value indicates the functionality of that variable in that design. For example, the Cable Moment and Racket design concepts has a value of 10 for the “Range of the lobes” variable. This means that the range of the lobes in that design are in theory the same as that of a cam that can be found on the market. Meanwhile, the Cleat design concept would have significantly less range, due to its design limiting how far the cam lobes can open. This would be due to the rope running through the cam that the lobes pinch needing to get taut quickly in order for the cam to function, which can be seen in Figure 20 in Section 4.3.

| Attribute | Importance | Cable Moment | Piston | Cleat | Ratchet |
|---|---|---|---|---|---|
| Range of lobes | 0.20 | 10.00 | 5.00 | 1.00 | 10.00 |
| Mechanism size | 0.25 | 10.00 | 3.00 | 1.00 | 4.00 |
| Force applied to rock | 0.25 | 10.00 | 3.00 | 7.00 | 1.00 |
| Single side loading | 0.10 | 1.00 | 1.00 | 1.00 | 0.00 |
| Manufacturability | 0.10 | 7.00 | 1.00 | 5.00 | 2.00 |
| Weight | 0.10 | 7.00 | 5.00 | 10.00 | 3.00 |
| Total Score | | 6.15 | 2.375 | 3.8 | 3.75 |

Table 1: Design matrix comparing various innovations for a cam

This same idea applies to all the variables and design concepts involved. The mechanism size refers to how large the cam is. Since the idea is to redesign micro cams, if the mechanism is too large it might not be applicable to the design as it would prevent it from being placed in smaller cracks. The higher number associated with that variable, the smaller and more practical the cam size is. The next variable is the force applied to the rock. A higher value for this variable indicates that the force exerted by this design will be closer to or greater than of a cam on the market. For this variable, the cable moment design was far superior to the rest. While we believe that the piston and cleat designs may off increased force values, they were not close to the promise of the cable moment design due to it building off of an already functioning system. The ratchet idea would not increase the force of the cam, only preventing it from retracting in the crack which would only act as more of a worst-case-scenario safety measure.

The next three variables all have less importance than the previously discussed three but are still vital to the creation of the cam. The first of the lower weighted variables is their ability to perform single-sided loading. Single-sided loading was an extra feature we wanted to cams to possess if possible, although it was not necessary. All three design concepts scored poorly in this category. The next variable was the design's manufacturability. The higher the number, the easier it would be to create the cam. The cable moment and cleat designs scored high due to them adding no more moving parts than a cam available on the market would already have while the piston and ratchet designs scored poorly due to having incredibility small mechanical systems that would be incredibility difficult to create. Lastly, the final variable was the finished product’s physical weight. Cams are meant to be as light as possible without sacrificing strength, so for this variable a higher value meant a lighter system. For the first time on the table, the cleat design was the sole victor as it would have the least number of components compared to the other three designs, although the cable moment design was a close second.

Overall, the cable moment design won by a large margin. While all the values entered are completely theoretical and based on our thoughts, they are based in our knowledge and experience with cams and mechanical systems and the research that we had conducted earlier in the project. This design matrix only takes into consideration the design concepts and does not touch upon the material innovations. As described in that section, Section 5, the only truly viable option of the four presented was the rubber coating.

## 6.2 CAD Model

In the design the lobes are initial forced out by stet of 4 rigid links attached to a spring at the base of the thumb loop. Not depicted are the wires however they will run in the groves of the lob. The wires will be attached to the lobe with a pin and will run all the way down the stem through to the thumb loop. When the thumb loop is loaded the lobes will expand outward against the crack increasing the normal force and friction and therefore preventing movement. The final CAD model of the cam is depicted below in Figure 22.

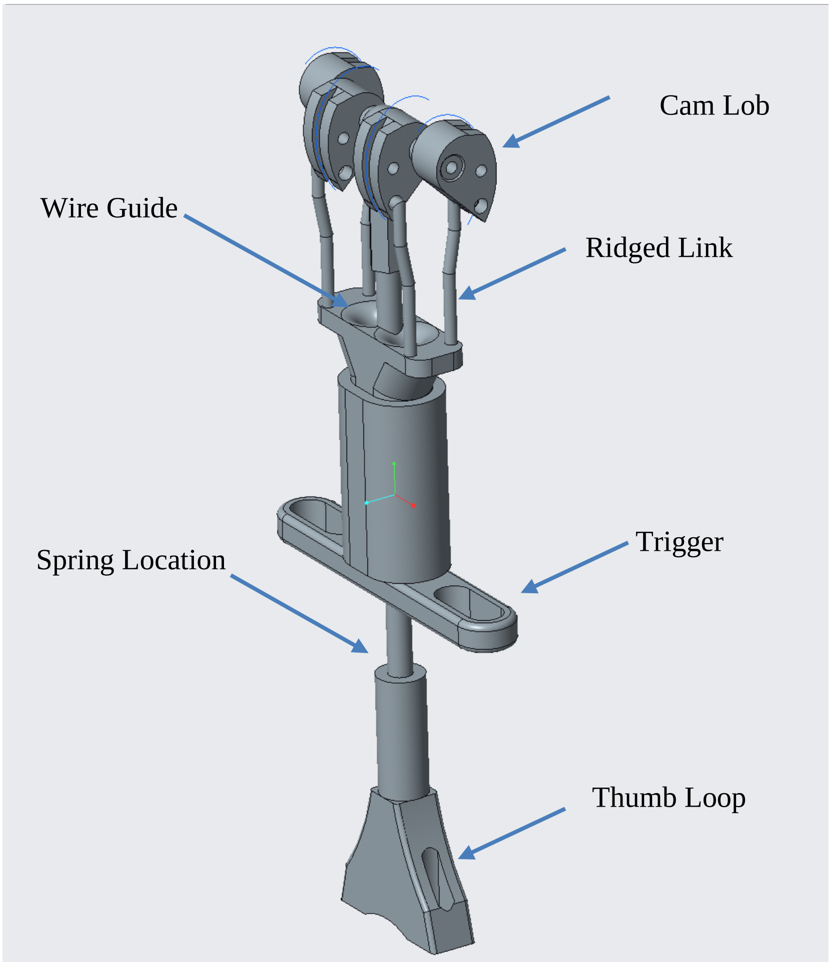



Figure 22: Initial Cad of the Cable moment cam

## 6.3 Design Analysis

We are in the beginning phases of our analysis of the cam. The first analysis we performed was to determine how much effect the moment had on the normal force. Figure 23 is the free body diagram for the cam. Figure 24 shows the equation for the normal force moment balance of the cam. With these equations we were able to prove that our design works

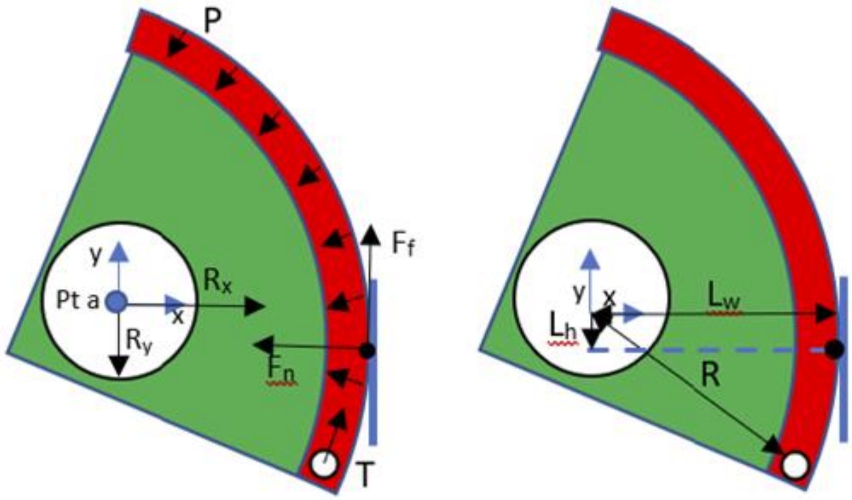



Figure 23: Free body diagram of a loaded cam lobe and the variable dimensions (left)

**Variables**

*Normal Force: $F_n$*

*X Direction Length from Center Axis to Cable Attachment: $L_w$*

*Y Direction Length from Center Axis to Cable Attachment: $L_h$*

*Radius from the central axis to the cable grove: R*

*Coefficient of friction: μ*

*Tension: T*

*The point moments are summed about Point a*

**Derived Variables**

$$Force\ of\ Friction: F_f = F_n \mu$$

$$Pressure: P = \frac{T}{R}$$

**Moment Balance**

$\sum M = 0$ Static equilibrium

$$\sum M_a = TR + F_n L_h + \mu F_n L_w$$

$$F_n = \frac{-TR}{L_h + \mu L_w}$$

Figure 24: Normal force equations with a moment balance

Using the normal force equation, we simulated various positions of opening of the cam. Beginning all the way closed and finishing at all the way out varying in increments of 0.5mm, the result from this graph is the exponential equation $F_n = 162.94e^{0.596x}$. The graph of this equation is shown in Figure 25. This exponential equation means that at the cams limit of expansion the holding force will be the strongest. This is important because failures occur in a cam when the lobes are at the upper limit of the cams range due to a lack of holding power.

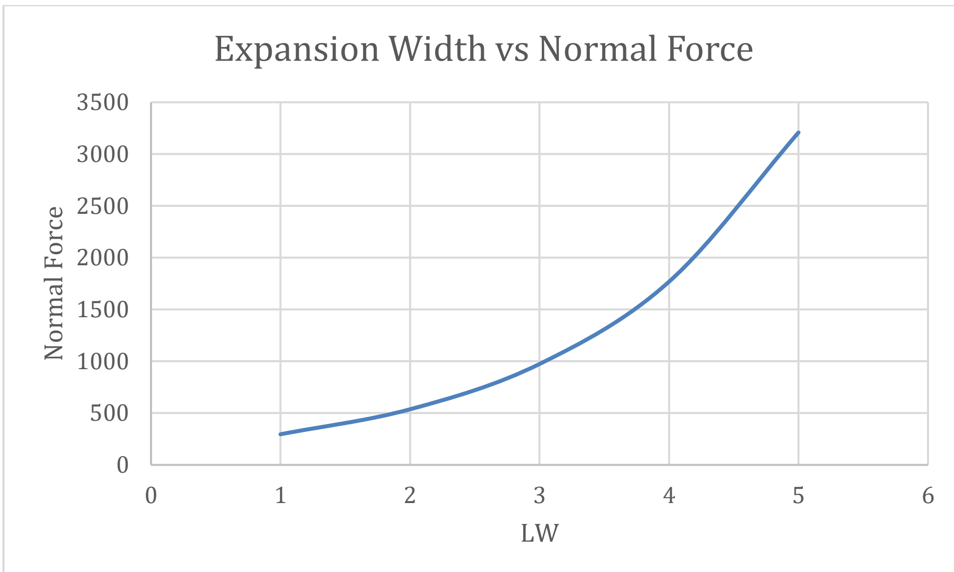



Figure 25: Graph of expansion width versus normal force (best fit solid line)

## 6.4 Functional Prototype

For our first functional prototype we 3D printed the components on a FDM 3d Printer. While the parts where slight out of spec with some finishing the prototype fit together well. The only parts that where not printed where he rigid links, the spring and the cables. The ridged links where made out of a paper clip and bent into place; the spring was taken from a pen and bent around the 3d Printed Stem; and the cables where striped from a piece of paracord. Figure 26 shows the assembled prototype. While there is significant friction between some of the 3d printed parts the cam does function as a spring-loaded camming device should and the moment cables provide a moment of the lobs. Figure 27 shows the device placed in a crack.

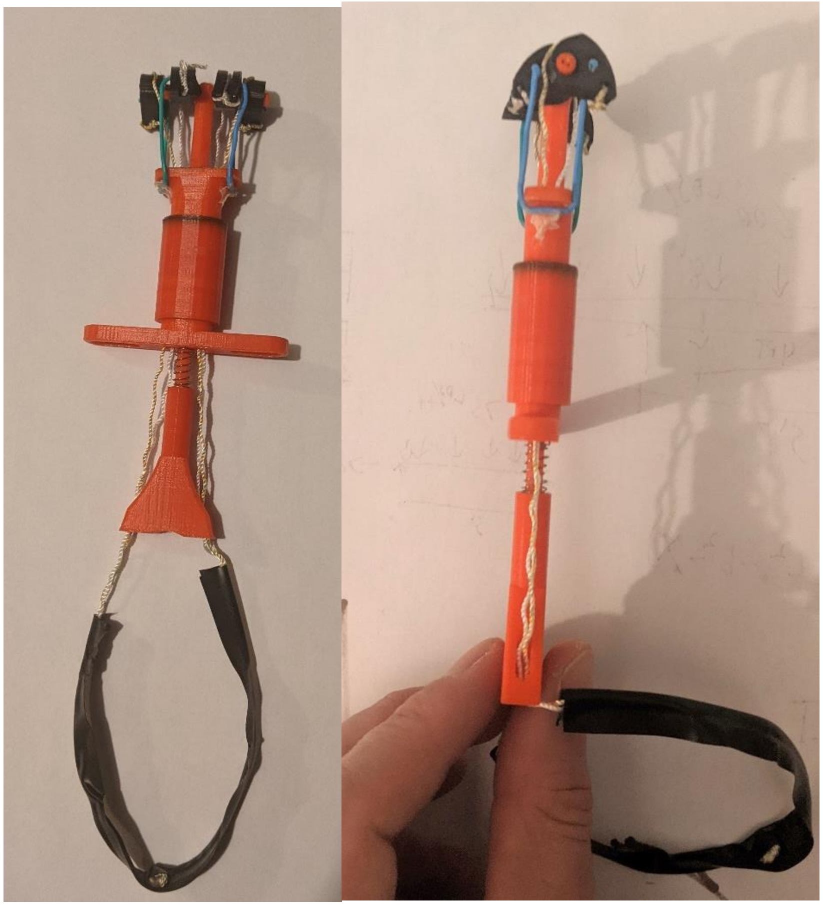


Figure 26: The Assembled Prototype in Front View (left) and Side View (right)

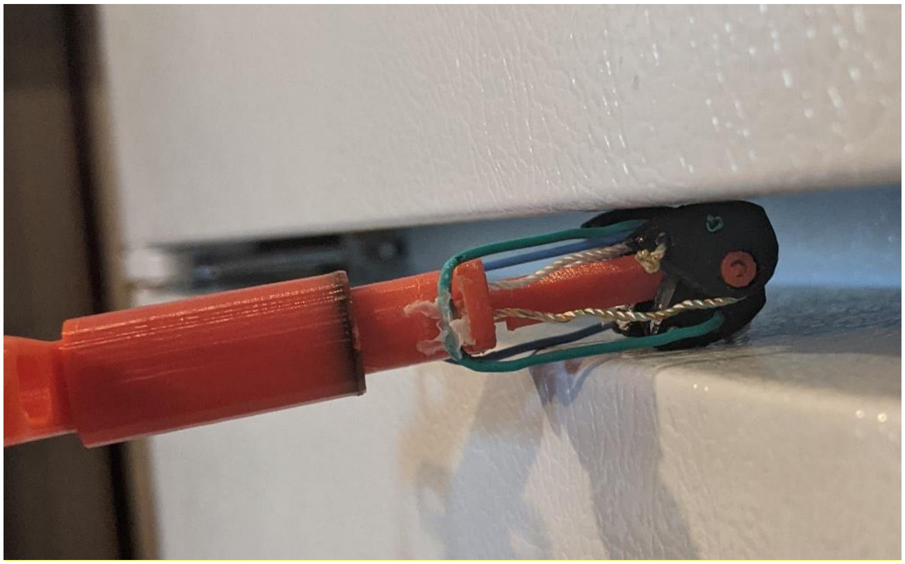


Figure 27: Prototype Placed in a Crack

## 6.5 Manufacturing Process

Manufacturing the cam consisted of CNC machining the aluminum parts. The machined parts where the thumb loop, lower trigger, upper trigger, stem axle and cam lobes. The tool paths were generated in the CAM software Esprit and All but the cam lobes where machined on the Hass Mini mill. These parts were simple and there was minimal machining challenge to them. The most complex part was the cam lobes. these where machined using a lathe technique called live tooling. Live tooling is a technique where 3 axis milling can be done both axial and radially on a lathe part. This requires an advanced machine tool; we used a Hass ST 30SSY. Once the parts machined, we then assembled the cams. In an industrial manufacturing setting the cabs are assembled via brazing however because we did not have access to these tools, instead we used a two-part epoxy. This method of assembly works for our design because the epoxied parts are never directly loaded. Once the machined parts where assembled, 16**-gauge** wire was used to make the ridged links. With these in place 1.5mm diameter dyneema wire was threaded through the cam then treaded through the holes on the lobes then tied off using a barreled knot.

## 6.6 Finished Cams

Figure 28 shows the assembled cam. Our cam weighs 52 grams this less than the competition which weights 69 grams. Our advantage comes from the lightweight materials we used specifically the dyneema cable.

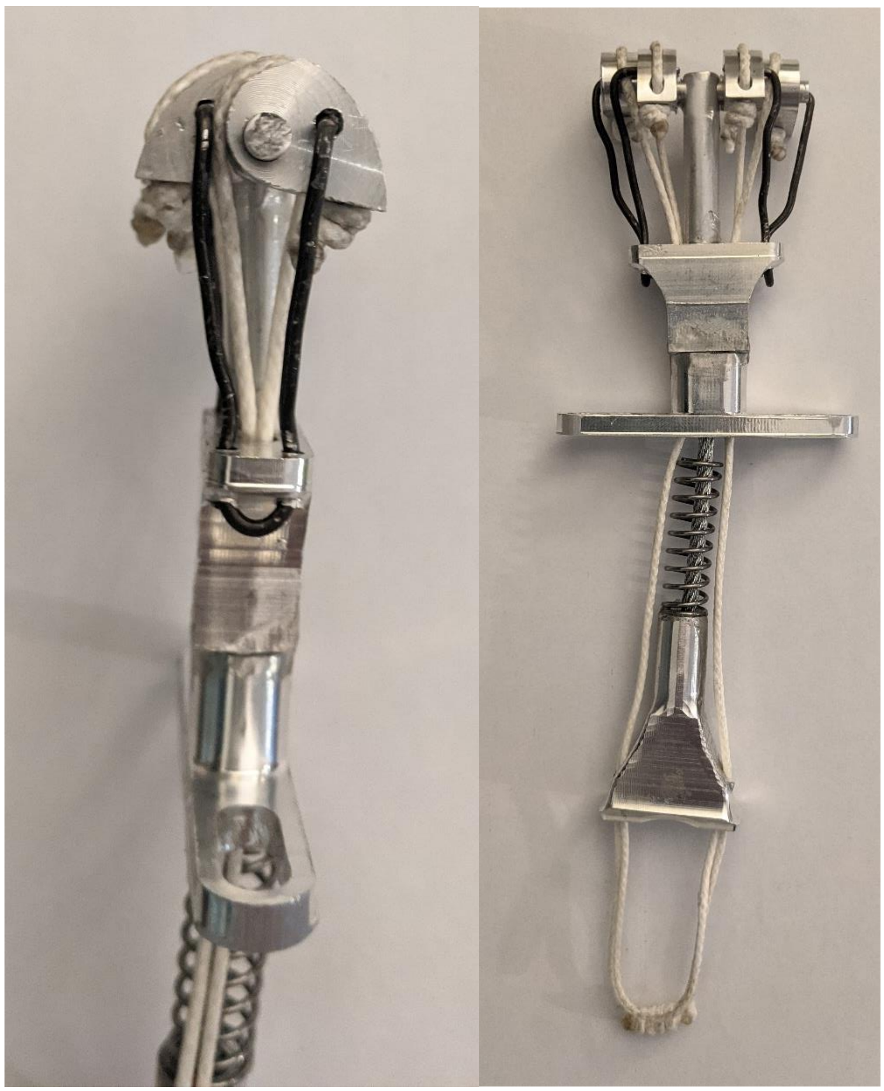


Figure 28: The Cable Moment Cam

# 7 Testing

In order to obtain the results that are required to confirm the effectiveness of our designs for improving the safety of micro cams, a series of tests need to be conducted. To conform with the UIAA standard for camming devices, previously described in Section 3.6, a standard tensile test in a simulated crack will be performed, but a series of more specific tensile tests were also be performed to best determine if our designs were successful. While the UIAA standard only calls for a straight down tensile test of the cam at specified lobe expansion widths, we also planned on conducting tensile tests in a simulated flared crack (International Climbing and Mountaineering Federation (UIAA), 2018). While this was not required, the idea behind the test was to demonstrate how the cam handles non-perfect conditions because not every crack encountered by a climber will be perfectly parallel.

In addition to the tensile tests mentioned above, cyclical tests were planned to be conducted at a maximum of 5kN in the parallel crack to simulate walking. The cams were going to be subjected to cycles of force between 2.5kN and 5kN and the number of cycles before walking occurs would be recorded.

## 7.1 Testing Apparatus

To perform the tests necessary to evaluate the cam's design, we used an Instron Testing System. The programming for the Instron was created using the software Bluehill.

### 7.1.1 Instron

Instron is a company based out of Norwich, Massachusetts that manufactures and distributes testing systems for mechanical testing. These machines are used in a wide variety of testing. These testing are primarily in the field of materials science and include the tension and compression of materials, fatigue and fracture testing, impact testing, and durability testing (Instron, n.d.a). A photo of an Instron testing system is seen below in Figure 29.

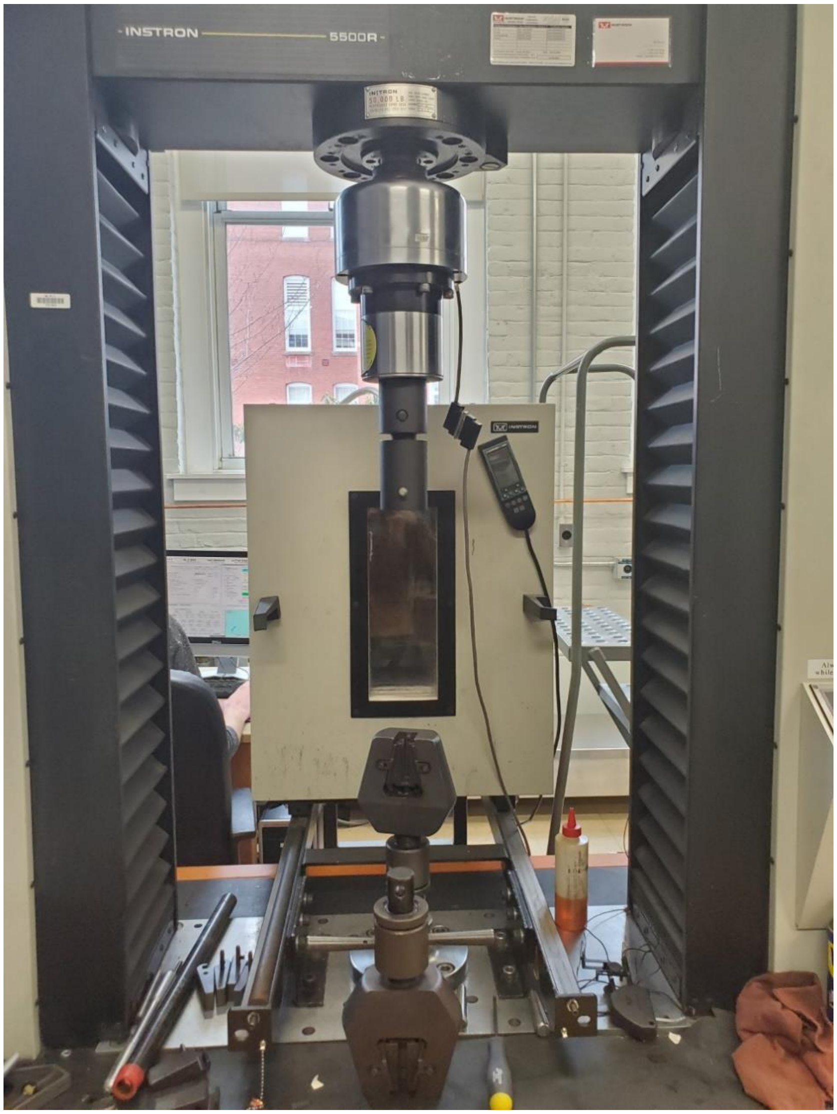



Figure 29: Instron 5500R testing system

For the purposes of our testing, we relied solely on the tension-related feature of the Instron system. This is because we only need to pull the cam apart in order to simulate the force of a climber falling on the cam. While the machine has a variety of different grips that can be used for different tests, we designed custom fixture that is compatible with the Instron to house the cam.

### 7.1.2 Bluehill

While the Instron is the mechanism for testing the strength of the cam, the software *Bluehill 3* was needed to program that Instron system (Instron, n.d.b). Bluehill 3 is a software developed by the company Instron for their Instron systems. The program is used to tell the Instron systems how to carry out tests through a series of fill-in-the-box components and drop-down menus. An example of this interface can be seen below in Figure 30.

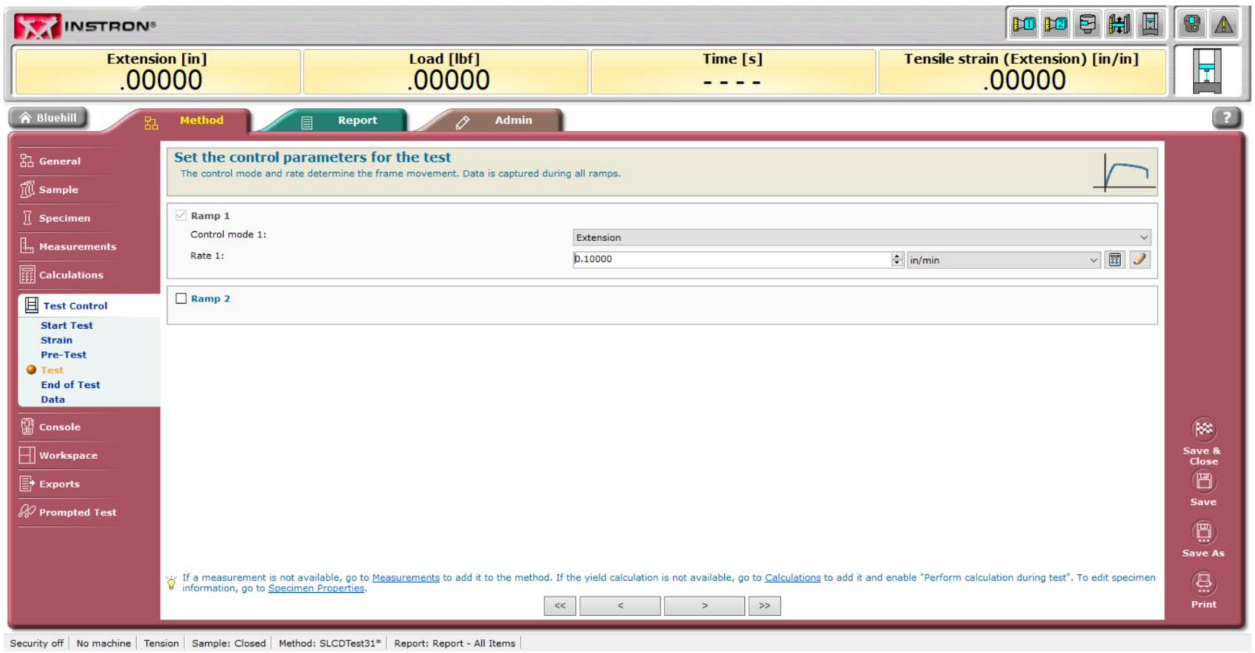



Figure 30: Bluehill program interface

For the purposes of our testing, we set up a very simple program using Bluehill 3. This program allowed for a tensile test at a given extension rate of 0.1 in/min. The Instron continued to pull on the cam until a force of 5kN is reached or the value of the force drops by 40% or more. The force dropping by 40% or more is a constraint because it indicated a breakage in the system. An immediate drop in force of less than 40% would more likely only be the walking of the cam in the fixture. While the program was running, it recorded the data of the time, force, extension of the Instron in inches, and the point within all those data points at which the cam breaks.

## 7.2 Tensile Testing

To perform the tensile tests, we used the Instron Testing System located on the WPI campus in WB113. The Instron allowed for the force of a fall, in the case of the project 5kN, to be simulated in a controlled environment. A set of custom fixtures were designed to be mounted within the Instron that are capable of simulating a crack. The Instron pulled the custom fixtures up with the cam engaged inside of them while the cam is held in place by its sling. The force exerted by the Instron was determined through programming done using the software Bluehill. The custom fixtures were created to have both a standard parallel crack and a flared crack. These fixtures are presented in more detail in Section 4.3 (Custom Testing Fixtures).

### 7.2.1 Standard UIAA Tensile Test

One of the tensile tests was the standard test as laid out by the UIAA. This was a straight down pull where the load linearly increases until either the cam fails or 5kN of force is successfully applied (International Climbing and Mountaineering Federation (UIAA), 2018). This linear progression of the force can be programmed into the Instron through the use of the program Bluehill. Bluehill graphed the results while the test was running and showed when the cam failed and at what value of force. The graph was also observed for any abnormalities that could represent when the cam walked.

### 7.2.2 Flared Tensile Test

Originally, we planned on conducting a tensile test using a flared crack to collect addition data outside of what was required by the UIAA standards. A custom fixture representing a flared crack was designed. This flared crack was designed to be at an angle of 28 degrees, the typical max range a cam can be in a crack and while still holding. While the standard UIAA test has constraints in place to determine the width of the crack the cam will be tested in, similar constraints do not exist for a simulated flared crack (International Climbing and Mountaineering Federation (UIAA), 2018). Because of this, the test was designed to load the cam at the midway point of the flared crack so that walking can be recorded if it occurs. The same Bluehill program would have been used for the standard UIAA tensile test.

This set of tests was abandoned very late in the testing stage of the project. While the information obtained from the tests would have been valuable, the third iteration fixture design for the flared crack did not provide enough friction for the cable moment cam to stay in. When we moved on from the third iteration fixture design to the fourth iteration fixture design, we were unable to conduct the flared crack tests because the fourth iteration fixture design used preexisting Instron grips that could only be used for the testing of the vertical crack.

### 7.2.3 Cyclical Loading Test

Early on in the project, we planned on conducting tests to observe how the cams would perform until a repeated, cyclical load. We wanted to conduct this test because when a climber falls, the rope stretches. When the rope stretches, it can cause a cyclical "bouncing"-like force on the cam once the climber has finished falling. This is commonly when cams walk. In order to see the effects of walking over a long period of time where falls may have taken place on the cam while it is in the crack, a cyclical loading test was designed for the cam. This test would linearly increase the force on the cam in the crack to 5kN, half of our original proposed maximum force. Once 5kN of force is reached, the force would linearly decrease to a force of 2.5kN. Once the force reached 2.5kN, it would have linearly increased back up to 5kN. This process would continue until a given number of cycles are completed.

### 7.2.4 Single-Sided Load Testing

Early on in the project, we planned on conducting tests to determine the holding power of the cam design using single-sided loading. For this test, the cam would only have two of the four lobes engaged in all the previously described conditions to test the strength in that scenario. The goal is to have the cam, when using single-sided loading, to be able to withstand 3kN of force. The Bluehill program would have been the same as the parallel and flared tensile tests, but with a maximum force of 3kN. This test would have been done to demonstrate how the cam can still be reliable even if placed incorrectly or in unideal conditions, such as a shallow crack. While this would have been a valuable addition to the data collected because most cams available on the market do not have single-sided loading, but due to time constraints on the project due to the COVID-19 pandemic this test was abandoned.

### 7.2.5 Coefficient of Friction Testing

Like the single-sided load testing, early on in the project we planned on collecting data on the different coefficients of friction between the aluminum cam lobes and different rock types. The different rock types used would have been granite, shist, and sandstone. While this testing idea did not progress very far, it would have been valuable data used in understanding how the cam lobes interact with common types of rock climbers may encounter in reality.

## 7.3 Custom Testing Fixtures

For the tensile test, we decided to design two separate testing fixtures. One simulated an angled crack, while the other simulated a straight up-and-down crack. This is largely due to cracks never being truly straight when climbing. It is very often that a crack is at an odd angle when placing a cam. Due to changes in the test’s restrictions the fixtures went through three major iterations.

### 7.3.1 First Iteration Fixture Design

Our first iteration of the custom fixture was to have a cubical holding rig with bars coming from top to bottom that would hold the rocks to simulate a crack. In between these rocks would be where the cam would be placed for the test. An initial concept CAD of the rods that hold the rocks is shown below. As seen in Figure 31, there is an area in the center to slide in your material of choice for the crack. There are also holes in order to properly secure the rock.

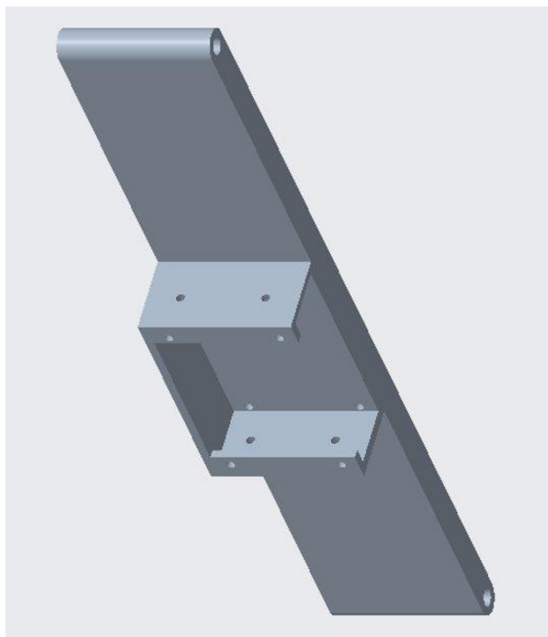


Figure 31: First iteration fixture for tensile testing

Within the cube, there would be two of these on either side going up and down, with pins going through them at top and bottom. In order to get the angled crack simulation, there would be rows of holes drilled along the top and bottom, in which you can place the pins. The holes would rotate along a central axis, as shown in Figure 32. This would allow for the distance between each of the crack walls to stay the same at the exact center when going from straight up and down to an angled crack simulation.

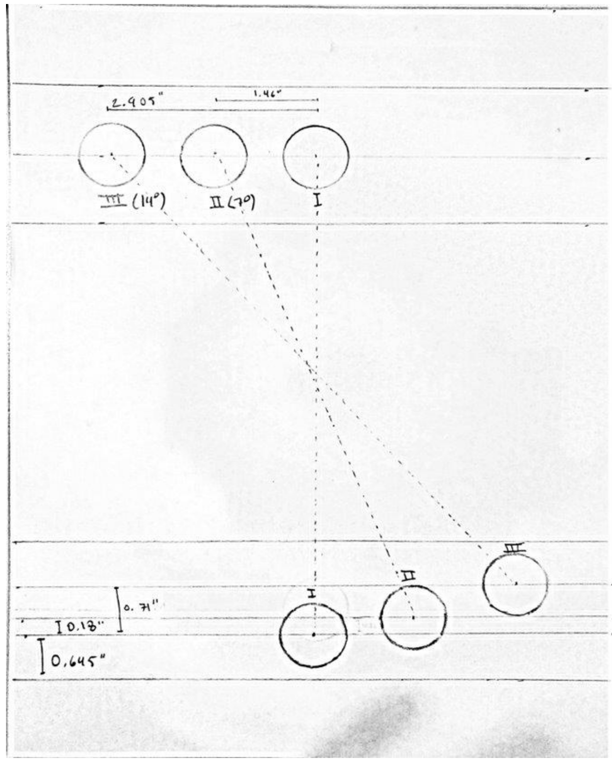



Figure 32: Holes on top and bottom rungs of initial cube testing rig

This design seemed to be a good option at first, however, we ran into problems when we had to consider how the holes would overlap when considering both sides, how we were going to construct the cube, and what instrument we are going to use to create the force for the tensile test.

### 7.3.2 Second Iteration Fixture Design

As the project progressed, we were able to gain access to the Instron located in WB113 on the WPI campus. This machine would be the most reliable why to simulate the straight-down forces required for testing. Taking this into account, the custom fixtures' second iteration uses the holding pin of an Instron to hang straight down. Similar to the previous design, there is still the ability to change the material for the crack, but there are two fixtures instead, each having a designated angle (one straight and one angled). As shown in the Figure 33, the rock material would be held on the left and right sides of the fixture. The cam would then be placed in the center and pulled directly downwards. This fixture is separated into two parts in order for easier machining and to allow for an easy connection to the Instron.

The two parts would then be bolted together and have the material of choice secured by bolts. The straight up and down version of this fixture is the exact same, but without the angle.

Figure 33: Prototype of the first iteration of the angled fixture

### 7.3.3 Third Iteration Fixture Design

After designing and 3-D printing the prototype for the second iteration of the fixture design, we met with the individuals in-charge of the Instron at WPI (Michael Collins and Davis Ladd). We got to see the Instron in person for the first time and needed to make some changes to the fixture design and the type of tests we were going to conduct. In terms of the fixture design, our perception of the connecting pin of the Instron used to hold the grips was incorrect. Because of this, the top of the custom fixtures needed to be redesigned, as shown below in Figure 34.

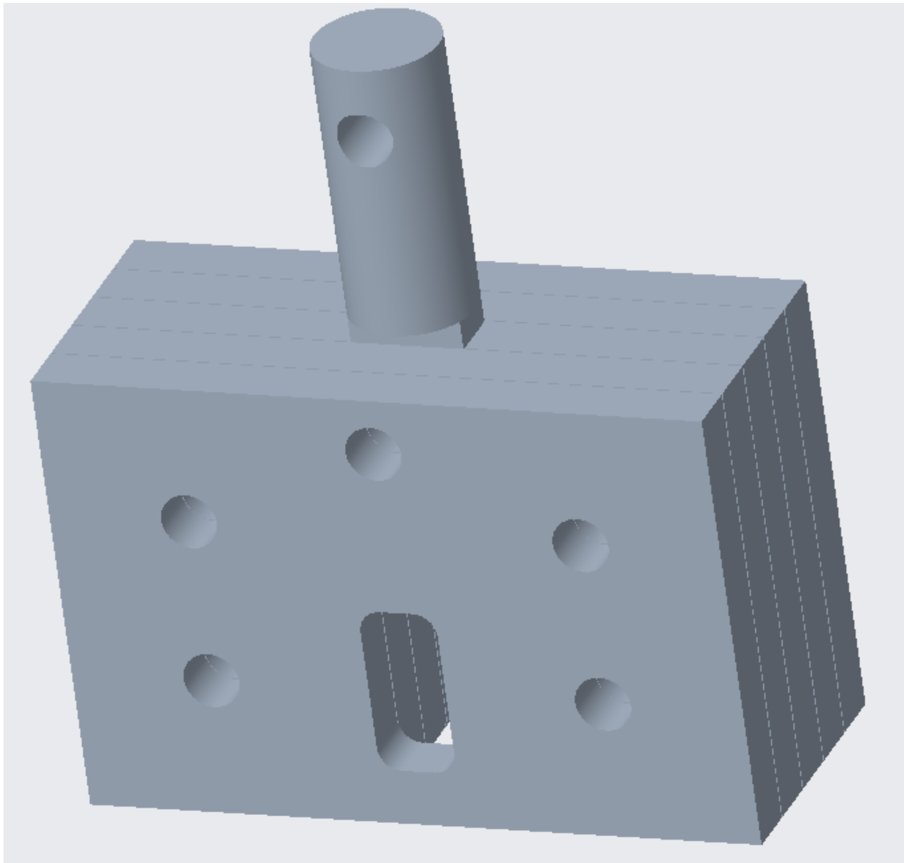


Figure 34: Third Iteration Fixture Design

The biggest change was to the material we were going to test with. As stated in Sections 4.3.1 and 4.3.2, we planned on using real rock samples in addition to the standard metal UIAA test in order to test the cams in more authentic conditions. Collins and Ladd were concerned about the rocks fracturing during testing and harming the Instron. Because of this, that feature of the fixture design was removed and the cam would only be tested against the metal surface of the custom fixture.

As shown above in Figure 34, the fixture is made up of 5 sheets of 0.5-inch aluminum. This was done to make the manufacturing process easier. Thicker material would have led to more chances for the tools to break and for mistakes to be made during the manufacturing process. The cam fits across the center three parts. We designed and manufactured two sets of the center three parts: 1 set with a parallel crack and 1 set with a flared crack. The two outer pieces can be used for both fixtures. Making the middle components interchangeable saved on manufacturing time and material cost. The top piece, seen individually in Figure 35 below, connects the fixture to the connecting pin of the Instron.

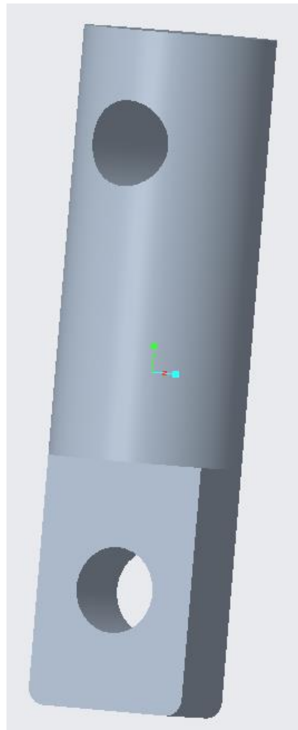
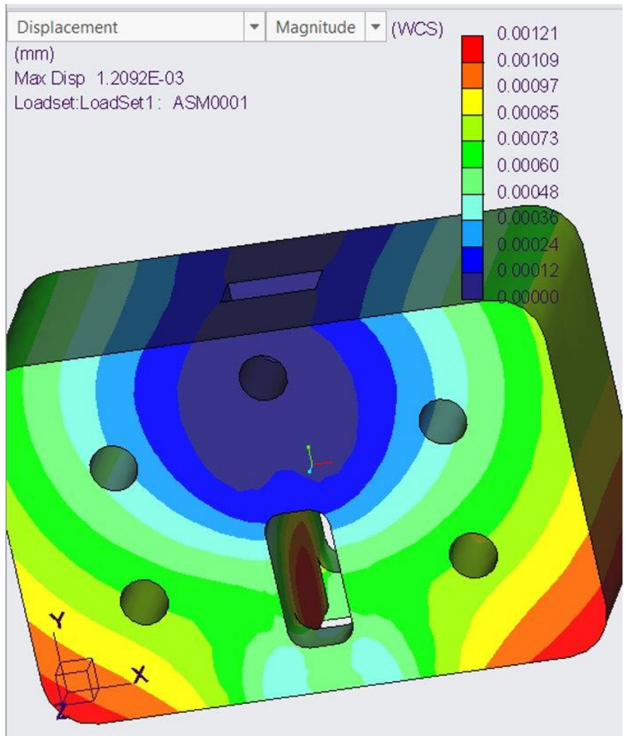
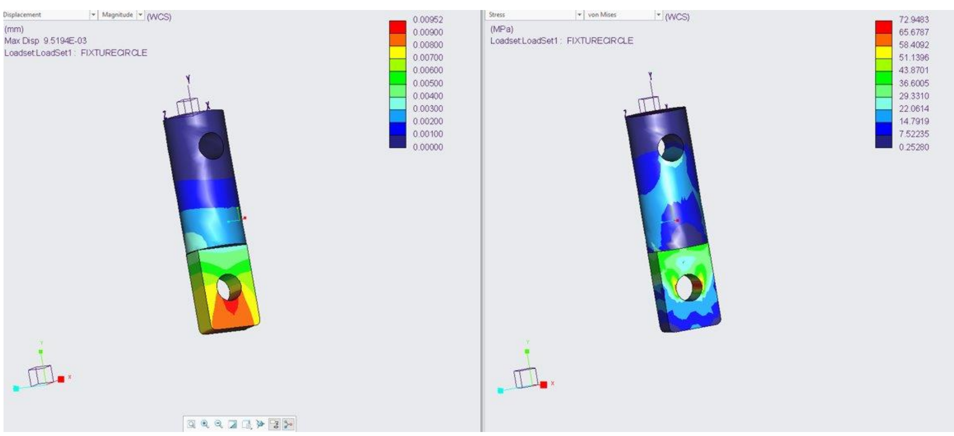


Figure 35: Upper section of third iteration fixture design

For this iteration, we conducted FEA analysis on the fixture to determine if it could support the 10kN of force the Instron will be exerting on it. The reason we conducted the analysis at a force of 10kN was to ensure that the fixture was not going to break and potentially damage the Instron with a safety factor of 2. These results can be seen below in Figures 36 and 37. While the fixture is made from aluminum and not steel like the traditional grips the Instron uses, the analysis demonstrated that the fixture would have little deformation during testing.



Figures 36 and 37: FEA analyses to cam forces inside the third iteration fixture design

Once the manufacturing of the fixture components was complete, the inside surface of the fixture that the cam lobes would interact with was roughed up to give it a surface texture, seen below in Figure 38. This was an important step because there would be very little friction between the two machined aluminum surfaces. To rough up the surface, we first cut shallow horizontal grooves using a hacksaw. Afterwards, the inside surface was sandblasted.

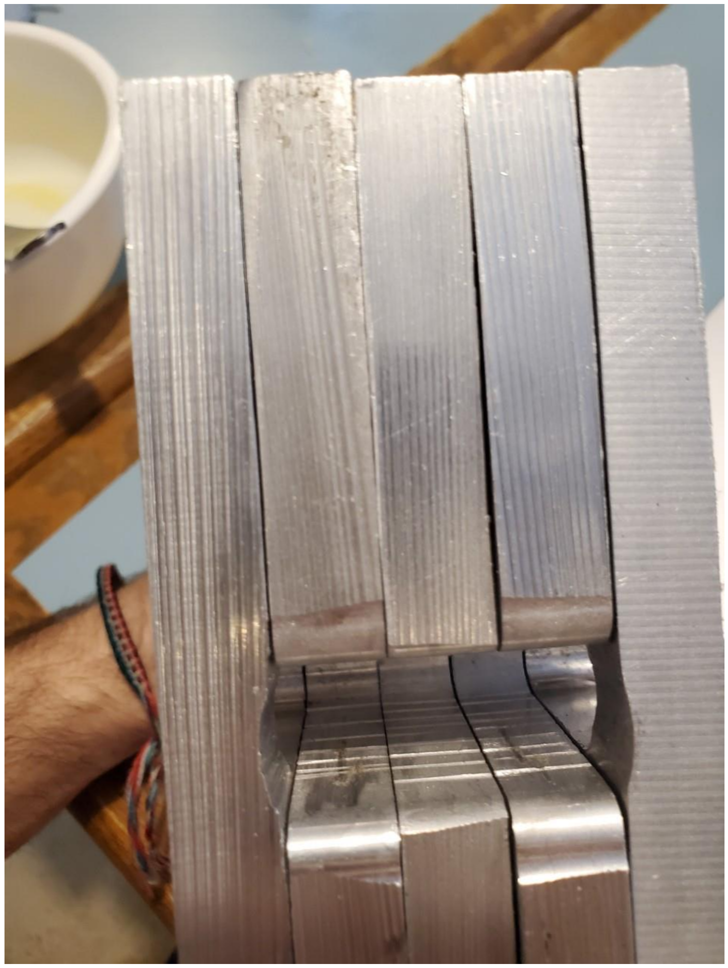


Figure 38: Interior of the Third Iteration Fixture Design with grooves

This issue of the surface of the fixture wall being too smooth due to both the lobes and the wall being machined surfaces was something we did not realize until late in testing. At first, we were confused as to why the cam lobes were not pulling on the inside surface of the fixture when the cam acted exactly as it was intended to. In a quick experiment, we used one of the textured vices in Washburn to create a simulated crack of the same size. Be engaging the cam lobes in the vice, we were able to lift the vice using the cam. We then applied this idea to the testing fixture, the first success of which can be seen below in Figure 39.

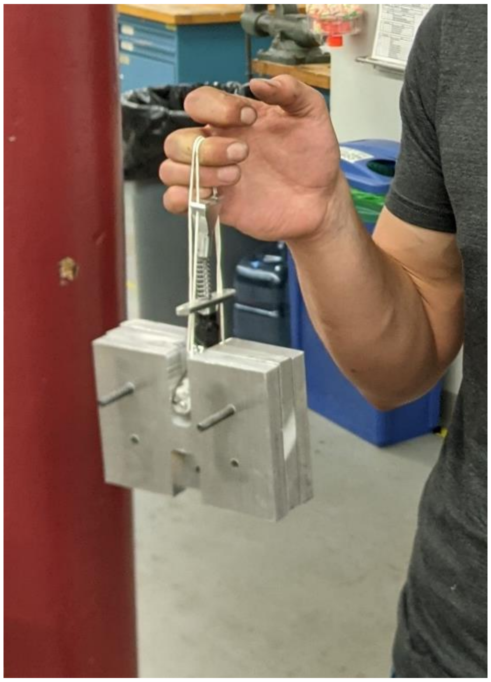


Figure 39: Cam lifting the third iteration testing fixture

### 7.3.4 Fourth Iteration Fixture Design

When we tested the third iteration fixture in the Instron, we observed the cam sliding. This sliding did not reflect the camming mechanism and was a result of the third iteration fixture. To address this, we used Instron grips that were currently in the lab. To make them work for our application, we fabricated steel plates that would fit inside the grips. The plates where mild steel, a 10-32 taped hole was drilled in the plates and was attached to the grips with a screw. This fixture while being the simplest ultimately ended up preforming the best. The reason this design worked better than the previous iteration was because the steel was less ductile than the aluminum. This allowed for the cam lobes to deform more than they did against the aluminum of the third iteration fixture design. The higher amount of deformation prevents excessive sliding of cam. The fourth iteration fixture with a cam in it is shown in Figure 40.

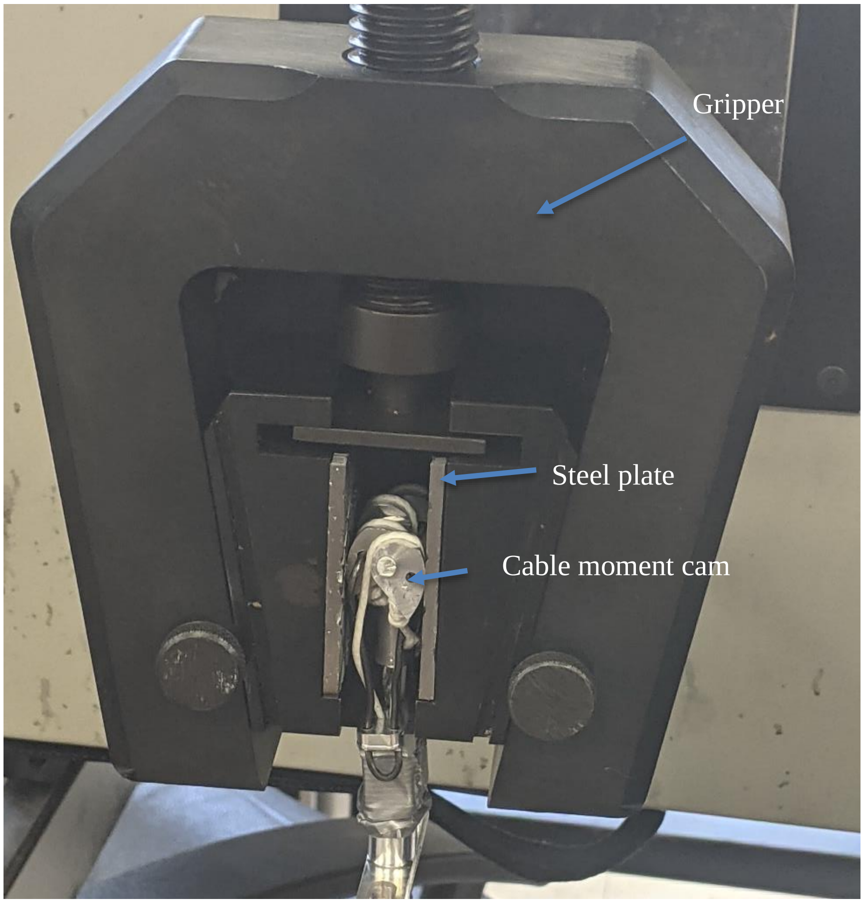



Figure 40: Fourth Iteration Testing Fixture

## 7.4 Testing Methodology

We conducted two rounds of testing. The first round of testing occurred on Tuesday April 13, 2021. The second round of testing occurred on Wednesday April 21, 2021. The difference between the two rounds of testing is the fixture that was used. The first round of testing used the third iteration fixture design, while the second round of testing used the fourth iteration fixture design. While the fixtures were different, the testing methodology was identical.

### 7.4.1 Testing Set-up

For conducting our tests, we used an Instron 5500R. First, we toggled the machine up using the control panel located on the right side of the Instron. Once we had significant clearance, we installed our custom testing fixture to the upper grip of the machine. This involved inserting the shaft of the fixture into the hollow shaft of the machine and lining up the holes so that a connecting pin could be inserted. Once the pin was inserted, the fixture was safely in the machine. The next step was to insert the cam being used for testing into the fixture. As the cams functioned correctly, by squeezing the trigger of the cam the lobes were able to retract and easily be placed inside the fixture. In the case for the first set of tests using the third iteration fixture design, sandpaper mesh was placed in between the cam lobes and the inside of the fixture to increase the coefficient of friction. This was because, even with the sandblasting and the addition of grooves into the fixture, the machined aluminum surface of the cam lobes had practically no friction with the machined aluminum surface of the fixture. The fixture containing the cam was then toggled down until it the loops of dyneema of the cam were in line with where the lower grip of the machine would be. Instead of installing a lower grip of fixture, a connecting pin was simply placed in the correct holes and ran through the loops of dyneema of the cam. This would hold the cam down as the upper grip of the Instron moved up and created extension during testing. The upper grip of the machine was then toggled up until the dyneema was taut. At this point, the test was ready to be conducted. This finished set-up can be seen below in Figure 41.

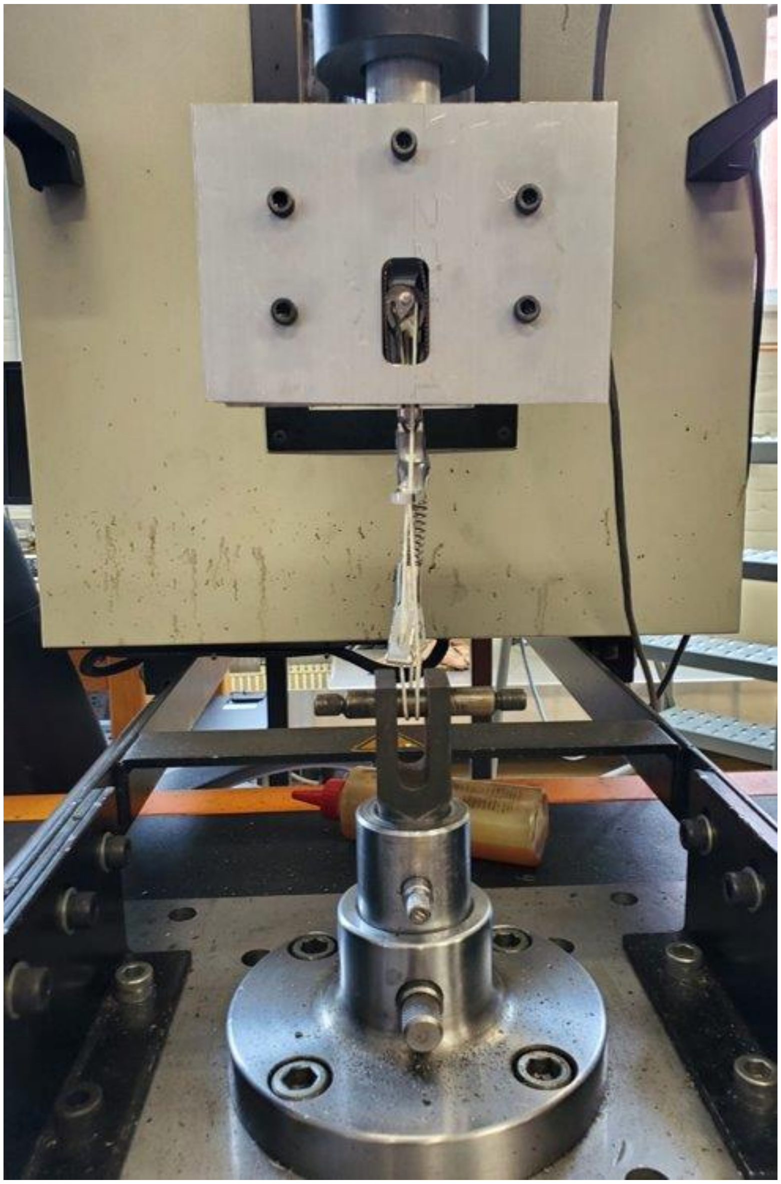


Figure 41: Testing Set-up using the third iteration fixture design

In regard to setting up the Bluehill program required for running the test, the Instron was already hooked up to a computer stationed next to the machine. We stored our Bluehill programs on a flash drive, so by plugging it into the computer we were able to open the Bluehill program we needed using the software Bluehill 3, which was available on that specific computer. The remaining set-up was simple as all we needed to do was run the program we made (referred to as a test method in Bluehill 3) and ensure that the data was being saved to the correct location. Before prompting the test method to run, the only input needed by us was to zero the extension and measured force by the Instron, which was done with two simple clicks in the program, and to set the rate of extension by the machine. The Instron we used in WB113 defaults to 0.06 inches/minute, but we were given permission to test slightly higher rates. We ran our tests at a rate of 0.10 inches/minute.

### 7.4.2 Test-In-Progress

Before we clicked to start the test, which is a function controlled by the Bluehill 3 software, we needed to put up a plexiglass shield between the machine and us while we observed the test in action. This was because of the potential for debris flying from the machine if the cam were to break suddenly and expectedly.

Once the start button was clicked, the test began, and the machine ran. We simply observed the cam in the fixture past that point. We could also watch the Bluehill 3 software on the computer because it graphed in real time a graph of the force measured by the Instron versus the extension of the Instron from the previously zeroed position. The readings and observations from these tests and programs will be discussed in Section 8.

### 7.4.3 Ending the Test

Once we noticed the cam slip out of the fixture or the force being displayed and graphed in the Bluehill 3 software begin to rapidly drop, we clicked to end the test on the software. This halted the extension of the machine. We would then save our data from the test in the software so that it could be analyzed at a later time.

To remove the cam from the fixture if it had not already been pulled out of it, we would toggle the upper grip down so that there was significantly less tension on the cam and the dyneema cable. Then we would squeeze the trigger on the cam to retract the lobes and easily remove the cam. While we kept all cams that were used in these tests, if the cam were still in manageable condition and could be repaired for future tests, we would fix it at a later date.

Once the cam was out of the fixture and if we had more tests to run, we would go back through the process of setting-up the test for the next trial with a different cam. Specifically, in the case of the first set of tests using the third iteration fixture design, the sandpaper mesh used in between the cam lobes and the inside of the fixture were replaced if needed.

# 8 Results and Analysis

As stated in Section 7.4, we conducted two different rounds of testing. While the same testing methodology was used, the two rounds of testing served different purposes. The first round of testing revolved around an initial test of the cam to ensure that everything functioned as it was intended to. This first round of testing used the third iteration fixture design. While results were gathered from the first round of testing, the second round of testing used the improved fourth iteration fixture design and gave more conclusive results.

## 8.1 First Round of Testing Results

For the first round of testing, we conducted three tests using two different cams. All three tests were conducted using the testing methodology described in Section 7.4 and used the parallel crack version of the third iteration fixture design. Only two cams were used across the three tests because the cam used in the second test was in perfect condition at the test's conclusion with no damage, so we decided to test it a second time in a row to observe how it performed.

### 8.1.1 Test #1

The first test used Cam #3, marked by the number 3 written on the thumb loop. For this test, we set the rate for the Instron's extension at 0.06 inches/minute, the standard used in WB113 for that machine. The cam experienced large amounts of walking and pulled out of the fixture at just below 2kN of force. While 2kN of force is just our observation, we cannot verify it as the Bluehill test method was set-up incorrectly and the data was not saved. This issue of the data not saving was fixed in all subsequent tests.

### 8.1.2 Test #2

The second test used Cam #2, marked by the number 2 written on the thumb loop. This cam is pictured below in Figure 42. For the second test, we added a thin layer of sandpaper mesh between the cam lobes and the inside of the fixture to try and increase the coefficient of friction during the test. Additionally, we changed the Instron's rate of extension to 0.10 inches/minute to make the testing process faster.

Figure 42: Cam #2 prior to the first round of testing

The test collected 22,212 data points over the course of 1110.55 seconds, which equates to 18.51 minutes. The Instron reached a maximum extension of 1.85092 inches which exerted a maximum load of 423.041 pounds of force. These measurements were set to be in customary units for testing purposes due to that being the default of the Instron. In metric units 423.041 pounds of force is equal to approximately 1.9kN, which is short of the goal of 5kN. The relationship between the force experienced by the cam and the extension of the Instron can be seen below in Figure 43.

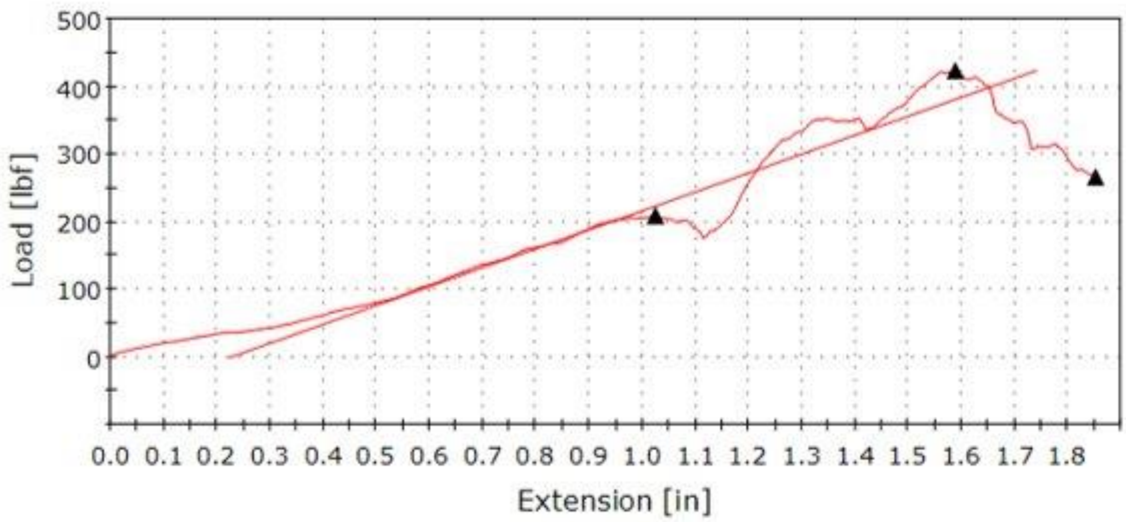



Figure 43: Relationship between the extension of the Instron and the force experienced by Cam #2 during Test #2

In the aftermath of the test, the cam did not fully slide out of the fixture. We stopped the test once the load started to rapidly decrease in an attempt to salvage the cam for later tests before it pulled out of the fixture and/or broke. Across the testing of the cam, there were two major incidents of walking that occurred: one at an extension of approximately 1.1 inches and a time of 11 minutes, and at an extension of approximately 1.4 inches and a time of 14 minutes.

### 8.1.3 Test #3

The third and final test for the first round of testing also used Cam #2 since it was undamaged in the second test. For the third test, we continued to use the thin layer of sandpaper mesh on the walls of the fixture to increase the coefficient of friction. The rate of extension continued to be 0.10 inches/minute.

The test collected 18,835 data points over the course of 941.70 seconds, which equates to 15.70 minutes. The Instron reached a maximum extension of 1.244 inches and exerted a maximum load of 528.106 pounds of force. In metric units 528.106 pounds of force is equal to approximately 2.35kN, which is short of the goal of 5kN. The relationship between the force experienced by the cam and the extension of the Instron can be seen below in Figure 44.

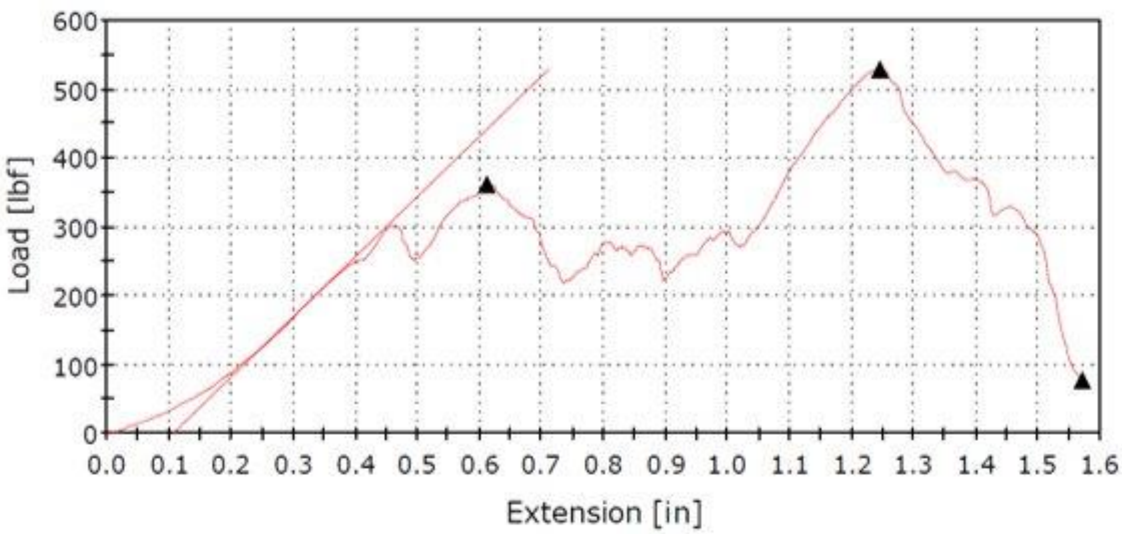



Figure 44: Relationship between the extension of the Instron and the force experienced by Cam #2 during Test #3

In the aftermath of the test, the cam did not fully slide out of the fixture. We stopped the test just when the cam looked as if it was going to pull out of the fixture. Unlike test #2we let the test continue to run after the load began to drop at an extension of approximately 0.61 inches and a time of 6.1 minutes. After a while of fluctuating at a lower load, the load began to increase again. This resulted in the maximum load achieved of 528.106 lbf at an extension of approximately 1.24 inches and a time of 12.4 minutes before the cam began to slide drastically and the load rapidly decreased.

Looking at the cam after the test, it was no longer intact. Two of the dyneema cables were broken, as shown below in Figure 45. One cable had pulled through the hole at the end of the cam lobe that it was tied into and another cable completely frayed at around the same spot.

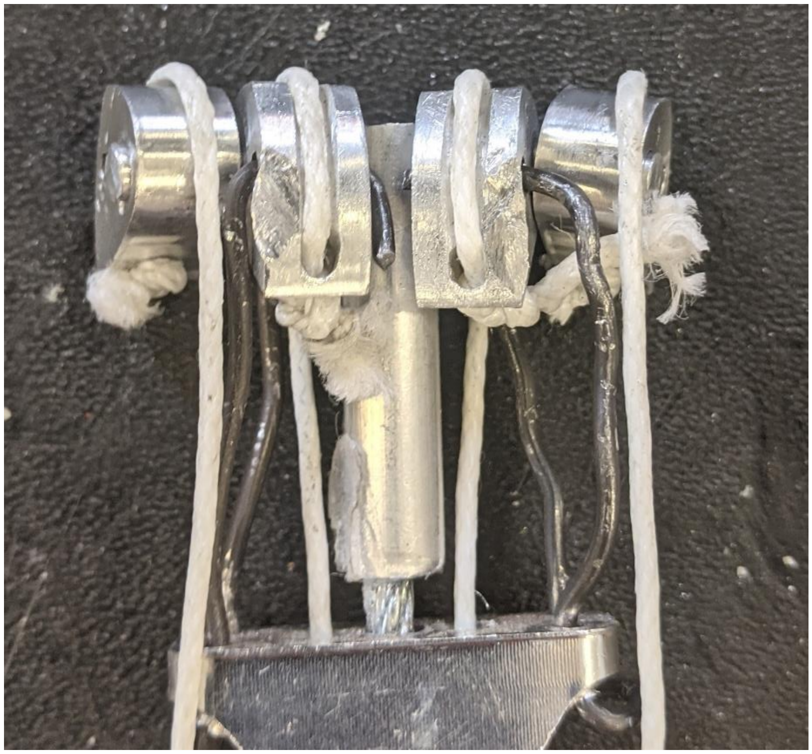


Figure 45: Damage to Cam #2 at the conclusion of the first round of testing

## 8.2 First Round of Testing Analysis

Disregarding the first test of the first round of testing due to a lack of tangible data, the second and third tests which both use Cam #2 have interesting data to present. Most of this data is not indicative of the ultimate performance of the micro cams, but it does give value insight on how to approach the second round of testing.

### 8.2.1 Cam Interaction with the Fixture

Across all three tests, the interaction between the cam lobes and the inside of the third iteration fixture was not a positive one. It seems as if the machined aluminum surface of the cam lobes had very little friction against the machined aluminum surface of the fixture, even with the added texture from sandblasting and cutting grooves. This can be observed on both the graphs for the second and third tests, which are shown below in Figures 46 and 47. At different points throughout both tests, the cam would walk for short periods of time. This walking can be seen on the graphs below (circled in blue). The interesting thing of note in these situations is that the walking eventually stops, and the cam begins to support and increasing amount of force again.

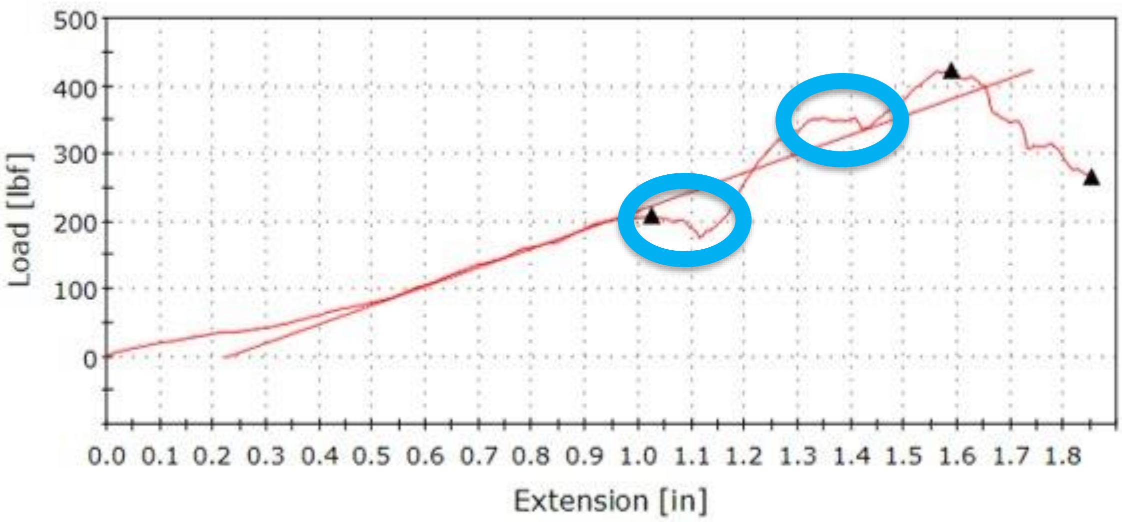



Figure 46: Major instances of walking of Cam #2 in Test #2 (circled in blue)

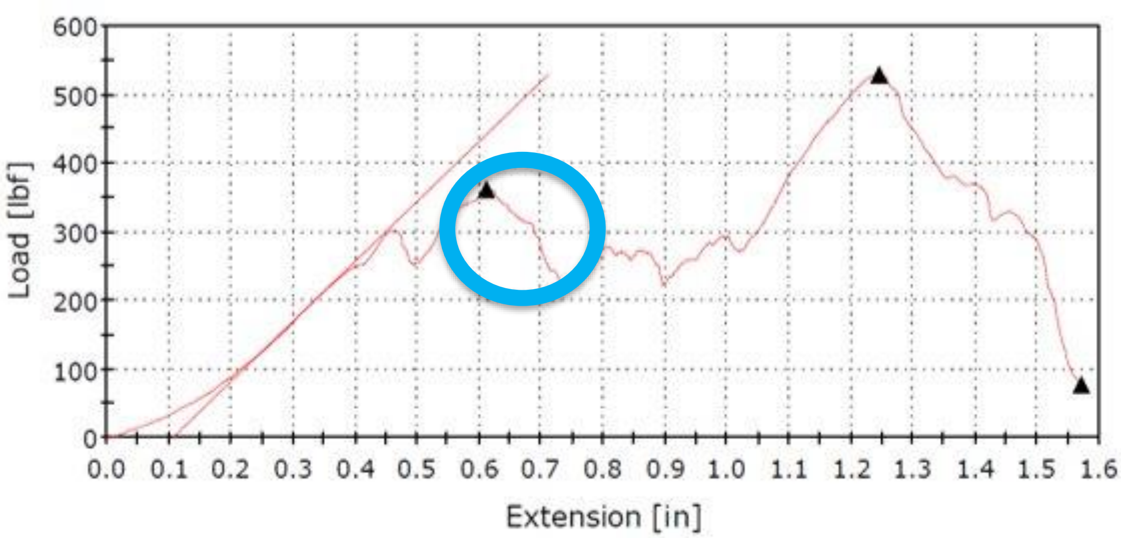



Figure 47: Major instances of walking of Cam #2 in Test #3 (circled in blue)

When this graphical data is added to our visual observations of the test, the answer to why this may be happening can become clear. When we were watching the test take place in real time, at the points in time where the graph indicates walking the cam was simply sliding down the inside of the fixture, even while still exerting a measurable amount of force (as seen in Figure 46 above). The sliding would even pull the sandpaper mesh between the cam lobes and the fixture with the cam lobes, showing that while it may have helped a small amount it is no replacement for real texture that is a part of the surface of the fixture. Additionally, when we removed the sandpaper mesh from the fixture at the end of the test, the places where both the cam lobes and the fixture made contact with it had completely disintegrated, leaving holes where material had once been. Over time the pressure and sliding from the cam lobes wore the sandpaper mesh down to nothing, which would remove its effectiveness in the test. At the points on the graph where the load began to increase after the period of walking, the cam lobes in the fixture had slid to around where the grooves had been cut into the fixture, giving the cam lobes something to grip onto. A side by side comparison of the cams position in the fixture at two different times in a single test due to walking can be seen below in Figure 48.

Figure 48: Composition of the position of Cam #2 at two different points in time due to walking during Test #3

From this data, it seems to get test results that are more telling of the real limits of the cable moment cam we had designed in the second round of testing we must create a new fixture that would allow for more friction between the cam lobes and the surface of the fixture. This finding would later result in the fourth iteration fixture design detailed in Section 7.3.4.

### 8.2.2 Damage to the Cams

During the first round of testing the most common form of damage to the cams was the knots in the dyneema cables pulling out. This was due to two issues with the manufacturing of the cams. The first is the holes drilled into the lobes to attach the cable were too large. Across all cams, the holes were too large, but some were larger than others. This was due to experimentation with the cam lobes regarding the different diameters of dyneema. Early in the assembly process, the dyneema we had received was too large for the grooves that were originally manufactured in the cam lobes. This caused a high potential for the dyneema to interact with the interior of the fixture. In an attempt to correct this issue, we both widened and deepened the grooves to accommodate the dyneema. In addition, we widened the holes where the dyneema was going to be tied into on some of the cams to accommodate the larger-than-expected dyneema radius. Ultimately, we moved on to a smaller diameter dyneema cable which made the modifications obsolete.

This issue was addressed in assembly by keeping the reduced hole diameter for the majority of the cams once the experimentation proved that a smaller dyneema diameter was required. The second issue was the knot used in this round of testing was an overhand knot. This cam un-tied when the cam was under load. To address this issue in the manufacturing of the cams for the second round of testing we used barrel knots to attach the lobes to the dyneema.

### 8.2.3 Analyzing the Force Exerted by the Cams

For the two successful tests conducted where data was recorded, the maximum loads recorded were 423.04 lbs and 528.11 lbs. This averages to 475.58 lbs. This is also equal to 2.12kN. The value of 2.12kN is far beneath the goal of 5kN.

By visual observation, the primary reason for this difference seemed to be due to the interaction between the aluminum cam lobe surface and the aluminum surface of the interior of the fixture. There did not appear to be enough friction for the lobes to engage and fully grab onto the surface.

As for why the two recorded tests obtained different values for the force, this is most likely due to the damage and alterations the cam received as a result of the tests. Since the same cam (Cam #2) was used for both recorded tests, the dyneema had already stretched a significant amount. Additionally, the knots in the dyneema that secured it to the cam lobes had been weakened due to the stress of the previous test. The major instance of walking that was present in Test #3, which can be seen below in Figure 49, was due to a knot in the dyneema becoming undone and slipping through the cam lobe. With the knot becoming undone, that specific cam lobe along with the cam lobe the other end of that strand of dyneema was tied into could no longer support any amount of force and became obsolete in applying force to the crack.

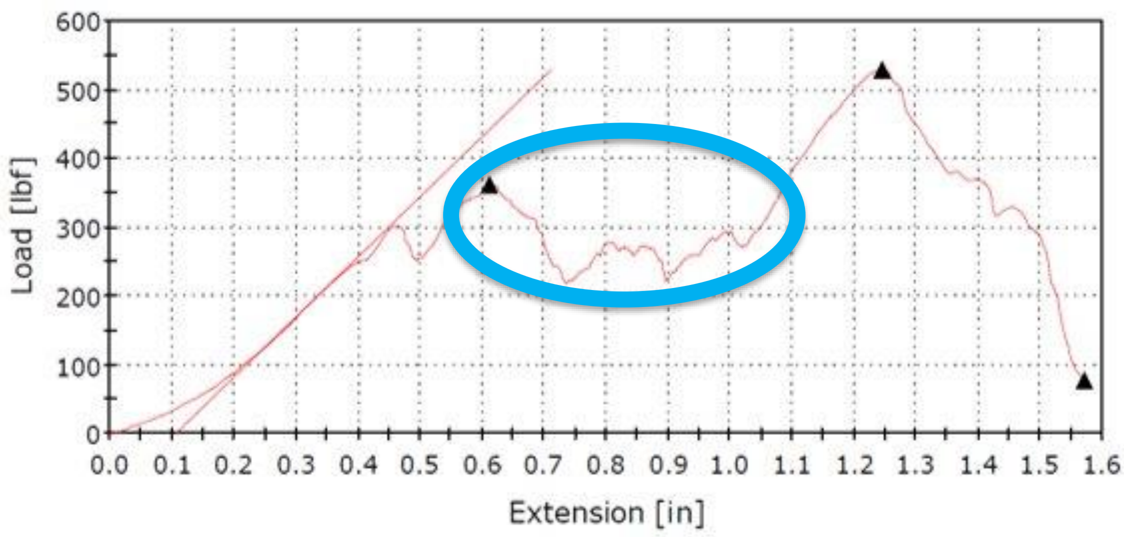



Figure 49: A major instance of walking by Cam #2 in Test #3 due to a dyneema cable becoming ineffective (circled in blue)

This instance of walking greatly altered the shape of the graph and making it have two large peaks instead of one that was obtained. While this is unideal because material failure could spell out harm for a climber using the cam, a positive result can be drawn from this failure. In the instance of material failure, only two lobes were engaged starting from an extension value of approximately 0.6 inches. While smaller instances of walking can be observed between extension values of approximately 0.7 inches and 1.05 inches, the cam ultimately did not fail during that time. Instead, at an extension value of approximately 1.05 inches, the load the cam was experiencing increased drastically and rapidly to the maximum value of 528.11 lbs. This is a promising result because it proves that the micro cam is capable of continuing to hold significant values of force even on only two lobes. With a more consistent assembly process and higher quality materials, it is likely that the cam would perform well with single-sided loading at even higher amounts of force.

While Test #2 did not yield an ultimate value of force as high as Test #3, it did have a more consistently shaped graph that was closer to the expected parabolic curve. This is due to a number of reasons. The first is because the dyneema had not yet stretched. In Test #3, the dyneema was already pre-stretched, so it ultimately took less time to reach higher values for the load which changed the slope of the graph. An example of this can be seen at an extension value of approximately 0.4 inches, just before the first major instance of walking in Test #3. At this extension value, Test #2 was at approximately 75 lbs while Test #3 was at approximately 250 lbs. Additionally, the graph for Test #2 was closer to the ideal shape because the dyneema cables only failed at the ultimate critical point, unlike Test #3 where the cables began to fail much earlier.

## 8.3 Second Round of Testing Results

For the second round of testing, we used the fourth iteration of the fixture. For this fixture, we designed a set of steel walls that can be placed inside the premade grip of the Instron machine. With this updated fixture we hoped to eliminate the premature slipping. In this round of testing, we used cams all three cams. The cams that were used in the first round of testing where restrung with new dyneema. Upon inspection of the previously used cam's lobes there was no damage to them, so we decided to use them again. The fourth iteration fixture in combination with these three cams produced the best results.

The first test was run on cam 1. This cam performed to a maximum tensile load of 321.75 lbf. While this is well below the rating needed to achieve the UIAA standard it did prove that our fixture was effective. This can be seen in the graph in Figure 50, the cam only slips once at 0.5 in of extension then re-catches. This is important because it validates our testing methods. This cam failed due to the knots pulling through the holes in the lobs. This issue is damage is similar to the damage seen in the first round of testing. We addressed this in subsequent rounds of testing.

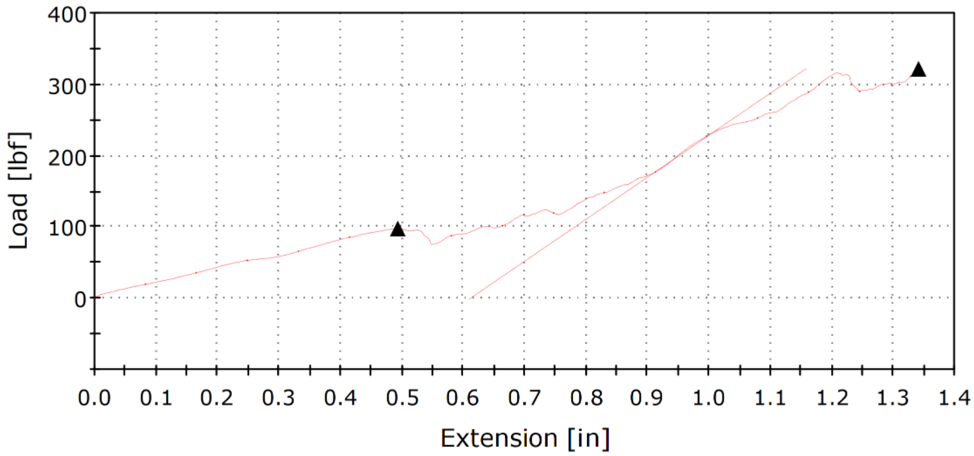



Figure 50: Relationship between the extension of the Instron and the force experienced by Cam #1 during Test #1

The second round of testing produced a better result, cam 2 failed at 538.76 lbf. This failure once again occurred due to the knots pulling through the cam lobes. While this is still below the UIAA requirement it shows that the cam has the potential to perform to a higher load. Shown in Figure 51, the stepped decrease from 1.5" of extension to ultimate failure shows the even when one cable fails the cam will still catch. This is important because in trad climbing once the cam holds the initial fall no more load is placed on the cam. Unlike in this test where the load is constantly increasing.

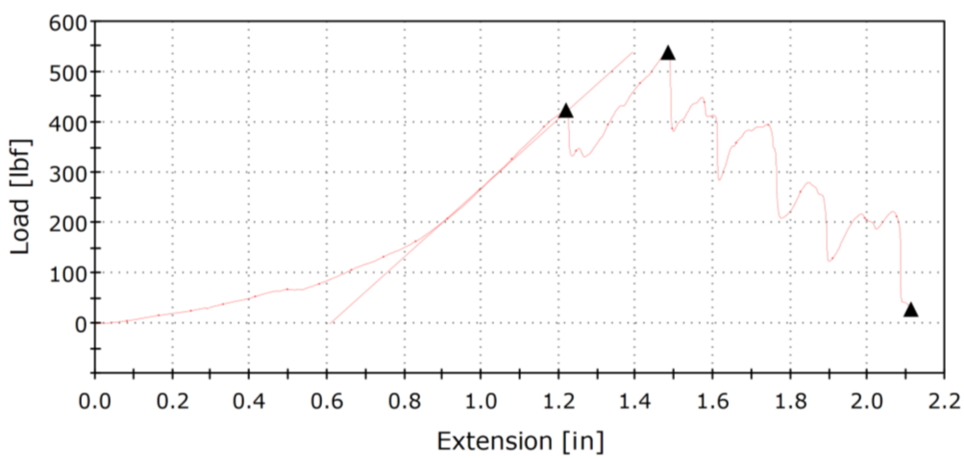


Figure 51: Relationship between the extension of the Instron and the force experienced by Cam #2 during Test #1 in the second round of testing

The third test produced our best result. Cam 3 held to a tensile strength of 761.41 lbf or 3.4kN while maintaining a consistent exponential curve as shown in Figure 52. The failure mode for this cam was the central axle bending rather than the dyneema pulling out. An image of the bent axle is shown in Figure 53. This is promising because it shows that the adjustments, we made to cam lobes was effective. We theorized that the bending occurred due to uneven tension across the dyneema wires.

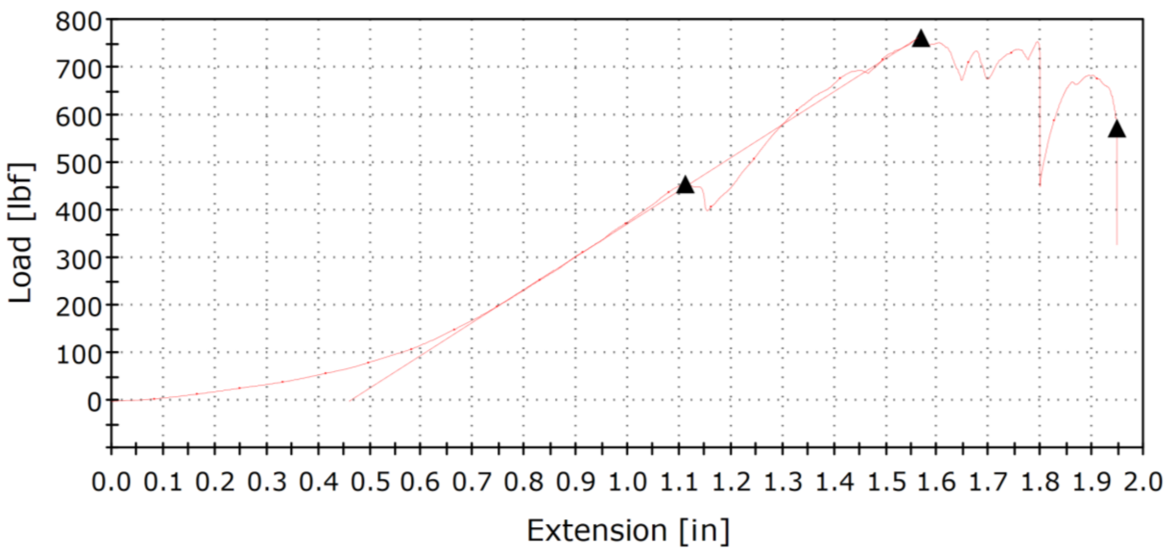



Figure 52: Relationship between the extension of the Instron and the force experienced by Cam #3 during Test #2 in the second round of testing

Figure 53: Picture of the bent axle after testing

After testing cam 3 we wanted to retest cam 2. We wanted to test these cams because the dyneema had already been entirely stretched by the previous test. We hoped that stretched dyneema would yield a more consistent curve. After re-tying the knots that had pulled out, we re-tested cam 2. Figure 54 shows the graph for this test. This test does show a steeper curve however it failed at 246.19 lbf far below the test 2's failure point.

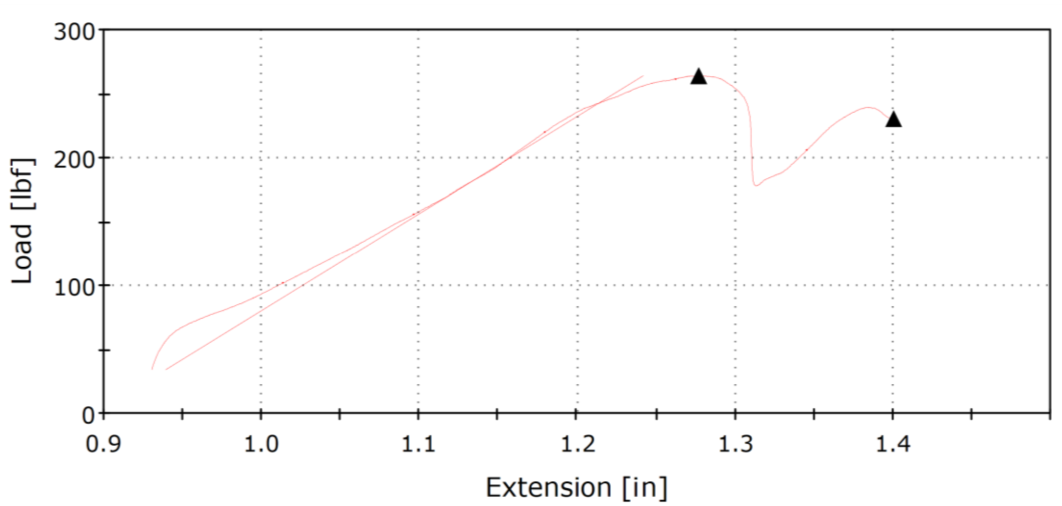



Figure 54: Relationship between the extension of the Instron and the force experienced by Cam #2 during Test #3 in the second round of testing

## 8.4 Second Round of Testing Analysis

While none of the cams achieved the required force of 5kN or 1124.04 lbf to meet UIAA standards the testing did prove the Cable Moment mechanism would work. When the cams slipped in the testing, they would consistently recatch and withstand a higher load. This means that when the cams walk or are placed improperly, the cams will recatch. This achieves our core goal of designing a safer micro cam. Additionally, the third test shows that when the cams are assembled correctly, they can withstand high loads. In that case the central axle bent. This could be resolved using a stronger material, such as steel, or larger diameter axle to decrease the stress the pin takes. One cause of the cable coming untied and slipping out was with diameter of the hole drilled in the lobe. In the first two tests, the hole drilled in the lobes to attach the dyneema was larger than the third test. In the second iteration of the Cable Moment Cam utilizing this smaller hole would be a solution to the dyneema pulling out from the lobes.

# 9 Conclusion, Reflection, and Recommendations

Making conclusions based solely on the results of the tests conducted, the cams we have manufactured would not pass UIAA standards and would not be allowed to be sold commercially. In order for a micro cam to be sold on the market, it must be able to hold the 5kN of force required in the standards. Our best performing cam was able to hold a force of 3.4kN, with others usually holding around 2 to 2.5kN. While the testing gave us promising results, the cams did not measure up to the required 5kN of force required for us to deem our design, the Cable Moment Cam, a true success. With that being the case, the results we gathered demonstrate that was still a lot of good in our design and that with multiple improvements, some of which would be in our control at WPI and some of which would only be truly applicable on a company-sized scale, the cams can be made to withstand a force of 5kN and be able to transition to the marketplace.

## 9.1 Cam Improvements

The initial design, testing and manufacturing of the Cable Moment Cam revealed several improvements to be made to the cam. Specifically, in the design, material selection, and the assembly of the cams. With these improvements to the cam, we believe that the cam could withstand the prerequisite 5kn force.

### 9.1.1 Design Improvements

The first set of improvements would be with the design of the cam. Specify deepening the grove that ran along the outside of the cam lobe. In its current state the grove is not deep enough into the cam lobe. This results in the dyneema cable rubbing along the rock or the testing fixture. This causes two problems the first is that the dyneema cable will wear out over time or could be cut by a particularly sharp rock. This is a large problem because if the cable fails the cam may not hold a fall. The second issue is that is reduces the effective radius if the cable is pinched. Reducing this radius will reduce the camming force and therefore the safety of the cam.

### 9.1.2 Material Improvements

All the metal parts of the cam were made out of 1060 aluminum. In our testing we found that two changes should be made to the material selection. The first is that the central axle should be made of an inelastic steel such as Grade A tool steel. This will prevent the central from bending when under high loads.

The second material change would be to change all of the non-load bearing parts to plastic. As the thumb loop, lower trigger and upper trigger do not see any of the load they could be made entirely out of plastic. This would reduce the weight of the cams, reduce the cost of the cams and, make manufacturing them easier. The one potential issue with this would be convincing the consumer that plastic parts on a cam would be safe.

### 9.1.3 Assembly Improvements

Another improvement to the cams would be a consistent manufacturing process. A consistent manufacturing process would improve the consistency of the tests and reduce the possibility of other parts of the cam contacting the testing fixture. We believe that if the cams where assembled to a tighter tolerance they would all preform to the level that the third cam performed to. This would further prove that the Cable Moment Cam's mechanism is an effective cam.

## 9.2 Testing Improvements

Throughout the testing process, we went through multiple iterations of testing fixtures before devising our fourth iteration which we used in the second round of testing. This fixture ended up performing the best out of all the iterations we had designed and is extremely similar to what is used by large scale companies to test their cams. Still, improvements to the fixture could be made.

### 9.2.1 Fixture Improvements

One aspect of the current test fixture that can be improved is the width of the simulated crack. UIAA standards dictate that specific lobe expansion widths must be tested depending on the maximum lobe expansion width of the cam. For the third iteration of the custom fixture, we designed the fixture to be the exact width that we would need. For the fourth iteration of the custom fixture, we used an Instron grip that already existed and was available in WB113. The only change we had made to the grip was the replacement of the inside steel plates for the purposes of testing. While the simulated crack the Instron grip created was approximately the same width as what the UIAA standard dictated, it was not exact.

In the future, manufacturing a custom fixture out of steel would combine the best aspects of both the third and fourth iterations of the custom fixture. Custom designing a fixture would allow for the creation of a UIAA approved crack width while keeping a greater amount of friction with the cam lobes due to its steel construction.

### 9.2.2 More Representative Testing

For this project, we used an Instron machine to apply a slow, linearly increasing load on the cam. While this worked for the purposes of this project and does not come into conflict with the UIAA standards, it is not entirely realistic to how cams are tested in the climbing industry. Although, with the resources that we had available on the WPI campus this was the most accurate test we could perform.

When a climber falls, their decent will not be at a rate of 0.10 inches per minute. They will fall much quicker due to the force of gravity. For this reason, companies that manufacture climbing cams do not steady with linear rates, but with quick impacts that simulate an immense force being applied to the cam over an extremely short period of time. With the resources we had available to us this was not possible, but in the future if more testing was to be done a large force experienced over a short period of time would be the most effective and accurate method.

# 10 Broader Impacts

## 10.1 Engineering Ethics

The first cannon of engineering ethics from the society of mechanical engineers states that "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties." (Council and Member Affairs/Board on Professional Practice & Ethics, 2012). By striving to improve spring loaded camming devices we are holding that cannon paramount. Our decisions were based around this primary goal of making a safer cam. The Cable Moment Cam meets this goal by bringing a new innovative technology to climbing market. While designing the cam we stuck to engineering best practices and followed the design process to ensure that the safest design was chosen. Additionally, we tested the cam to the UIAA standards.

## 10.2 Engineering Codes and Standards

The UIAA or International Climbing and Mountaineering Federation sets the standards for all climbing and mountaineering products.  To test the Cable Moment Cam we used standard UIAA-125 frictional anchors. This is the tensile test described in the testing section. It is important to follow these standards because it upholds the first cannon of engineering ethics. By complying to the standard, we did all that we could to ensure that the cams would be safe to use. Because the cams did not meet the standard, we know that we must improve the cam before ewe could bring it to market.

## 10.3 Societal and Global Impacts

The goal of this project is to improve the safety of micro cams by creating a new and improved design for climbers to use. With this new design, there will hopefully be less people being injured by mechanical cam failure and placement of a cam. Our design, the Cable Moment Cam, allows for the climber to have more wiggle room when placing a cam, therefore helping to decrease failure caused by poor placement, which is the leading cause of cam related injuries. Ideally, our design will spark new ideas in cam related designs and push cams to have a new level of safety.

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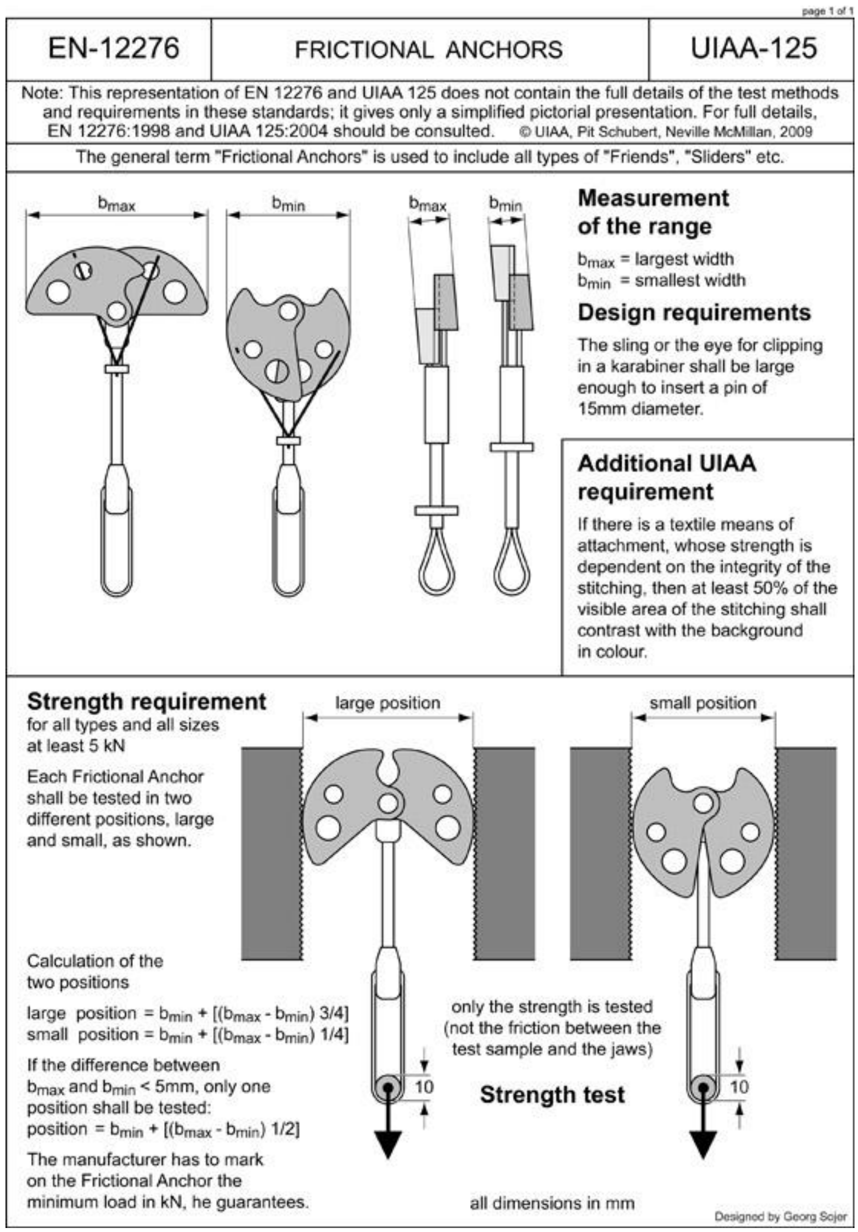
# Appendices

## Appendix A – UIAA 125-Standard

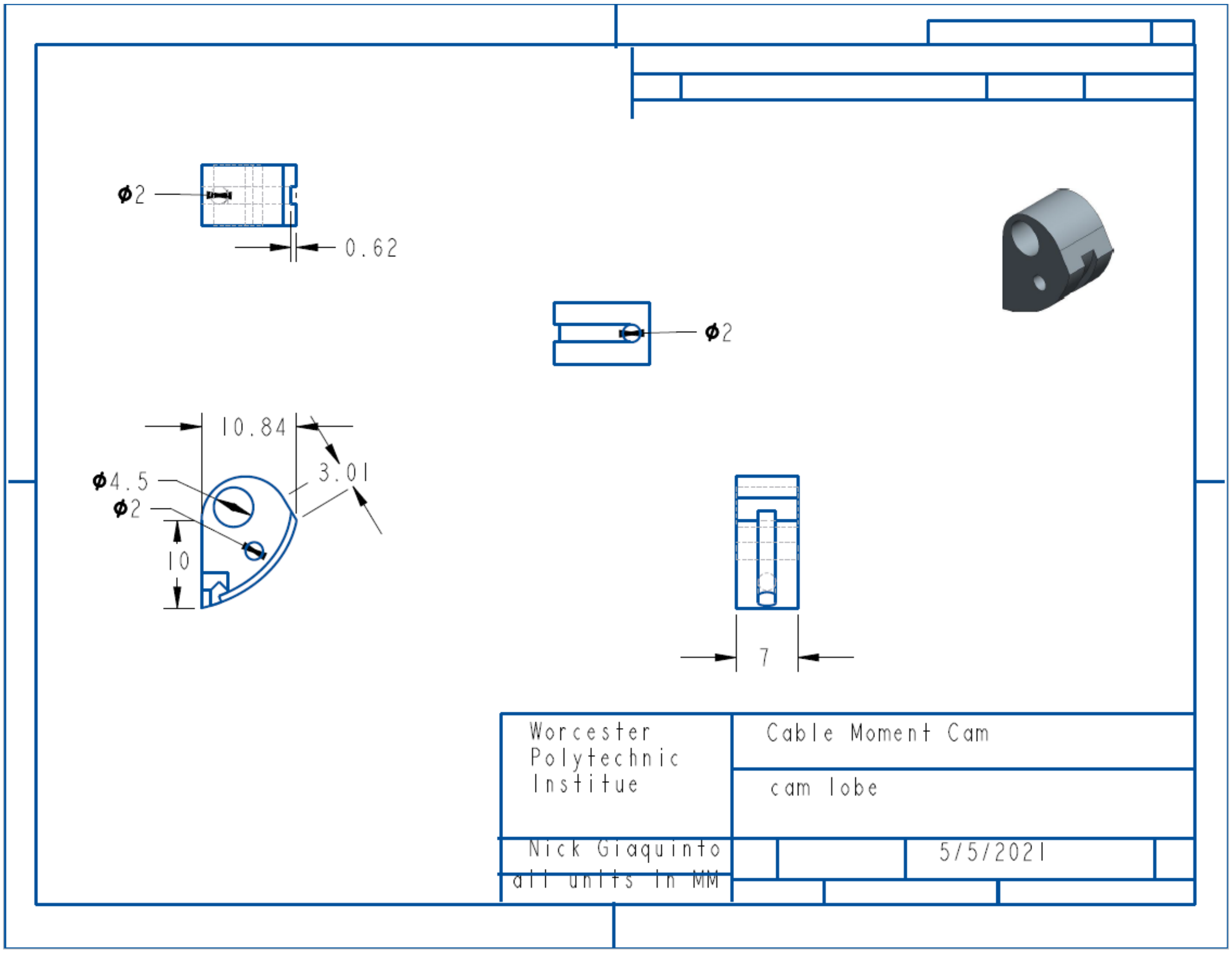



Source: International Climbing and Mountaineering Federation (UIAA). (2018, February). Frictional Anchors. Bern; International Climbing and Mountaineering Federation (UIAA).

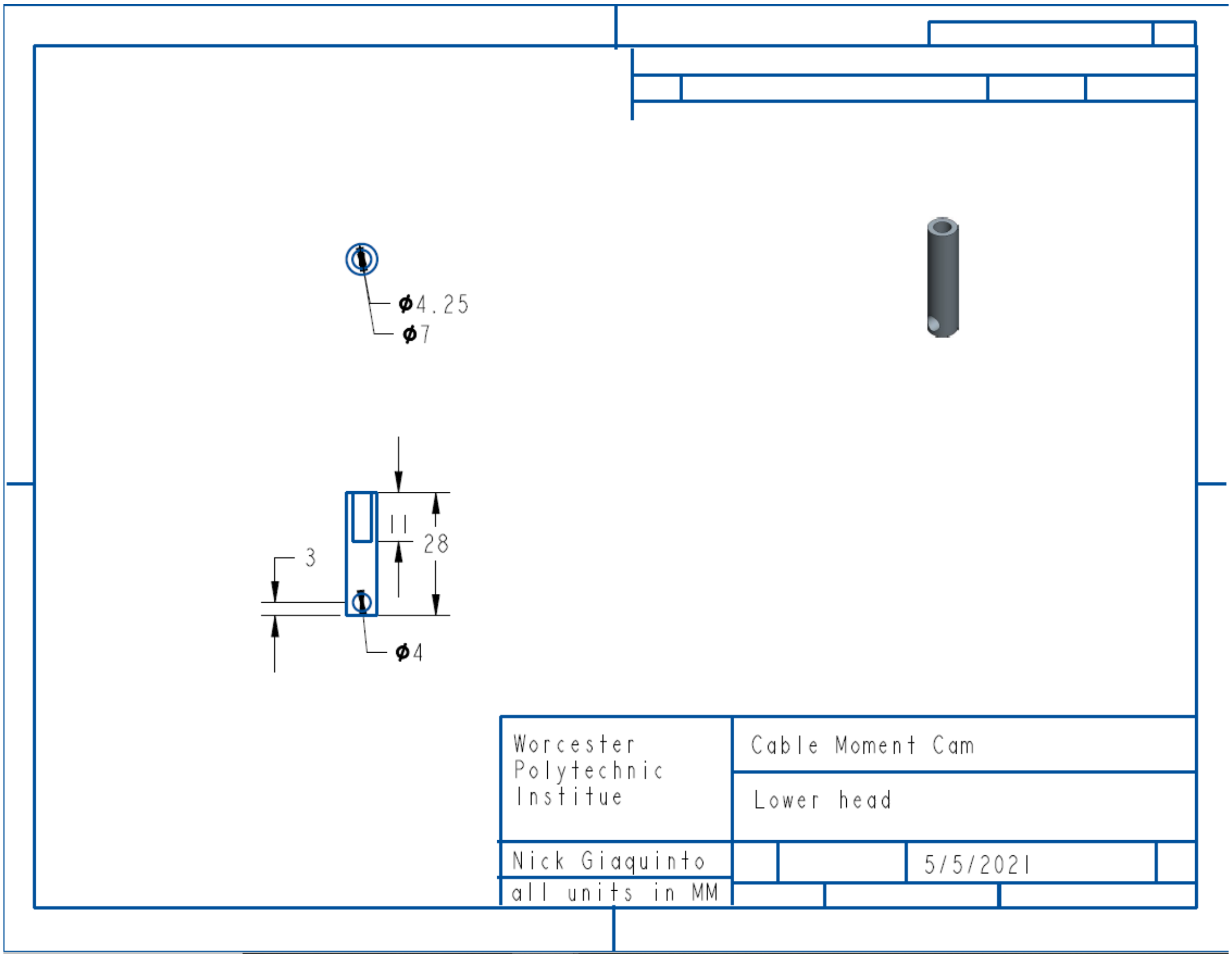
# Appendix B – Bill of Materials

| Part Number | Description | Quantity | Price |
|---|---|---|---|
| 9246K94 (McMaster-Carr) | Multipurpose 6061 Aluminum ½” thick, 6”x48” | 1 | $101.06 |
| 4634T33 (McMaster-Carr) | 6061 Aluminum 7mm Diameter 1’ long Rod Stock | 1 | $1.09 |
| 6940T11 (McMaster-Carr) | Multipurpose 6061 Aluminum Rod 4mm Diameter 1’ long | 1 | $9.19 |
| 9517K354 (McMaster-Carr) | Tight-Tol. Low-Carbon Steel Bar 1/8” Thick, 1-1/2”x1’ | 1 | $13.52 |
| 3461T78 (McMaster-Carr) | Wire Rope 7x19, 7/32” Diameter | 1 | $10.25 |
| 91251A553 (McMaster-Carr) | ¼”-20 Thread, 2-3/4” long, Partially Threaded Steel Screw | 1 | $11.48 |
| 95462A029 (McMaster-Carr) | ¼”-20 Thread Steel Hex Nut | 1 | $5.29 |
| 8975K437 (McMaster-Carr) | ¼”x6” 6’ long 6061 Aluminum Stock | 1 | $63.61 |
| 4634T31 (McMaster-Carr) | 5mm Diameter 3’ long 6061 Aluminum Rod Stock | 1 | $1.31 |
| 8974K15 (McMaster-Carr) | 1-1/8” Diameter 1’ long 6061 Aluminum Rod Stock | 1 | $8.05 |
| B01N6QD0H2 (Amazon) | 1.3mm Diameter Dyneema (Spectra) | 1 | $11.49 |

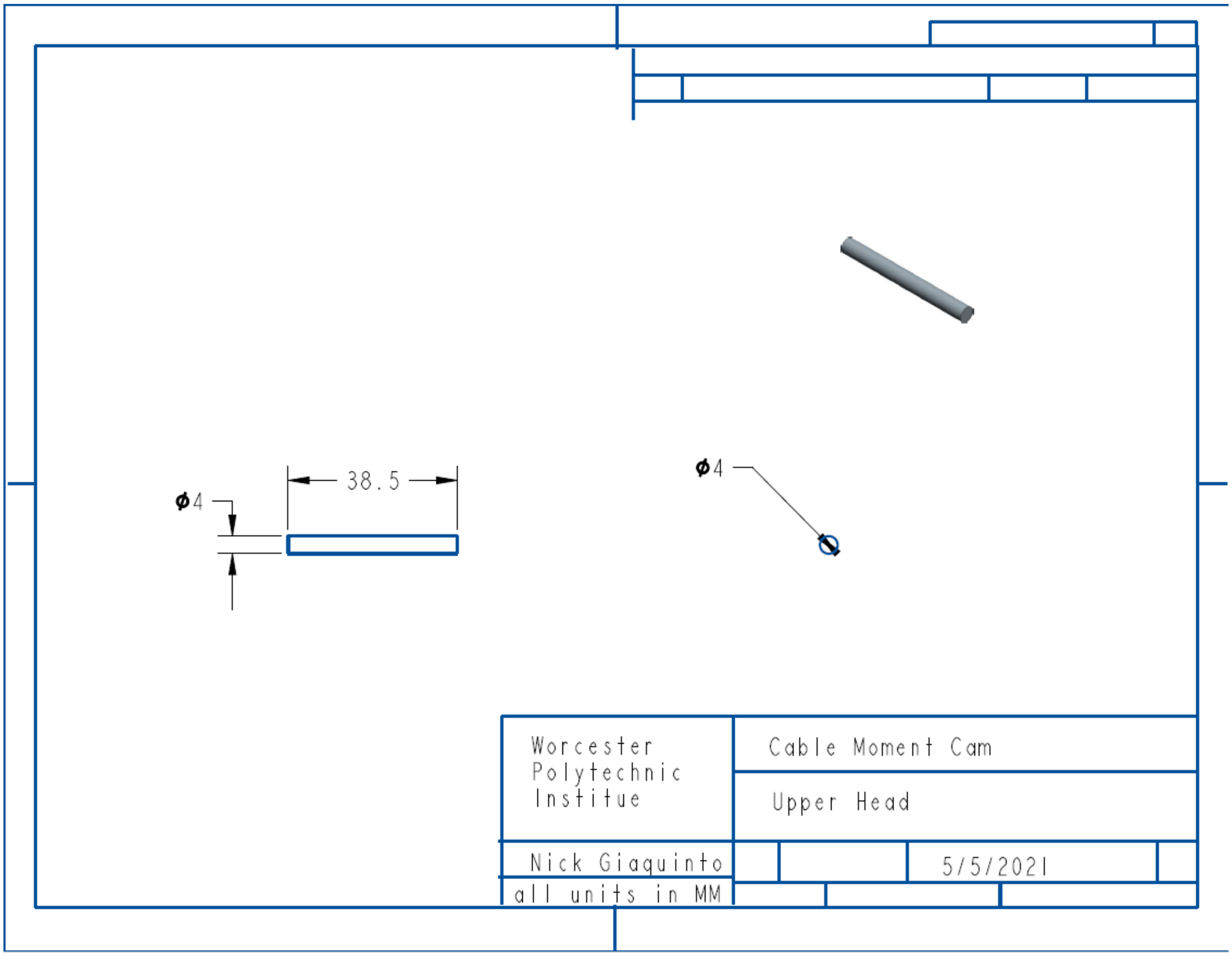
# Appendix C – Cam Lobe Drawing



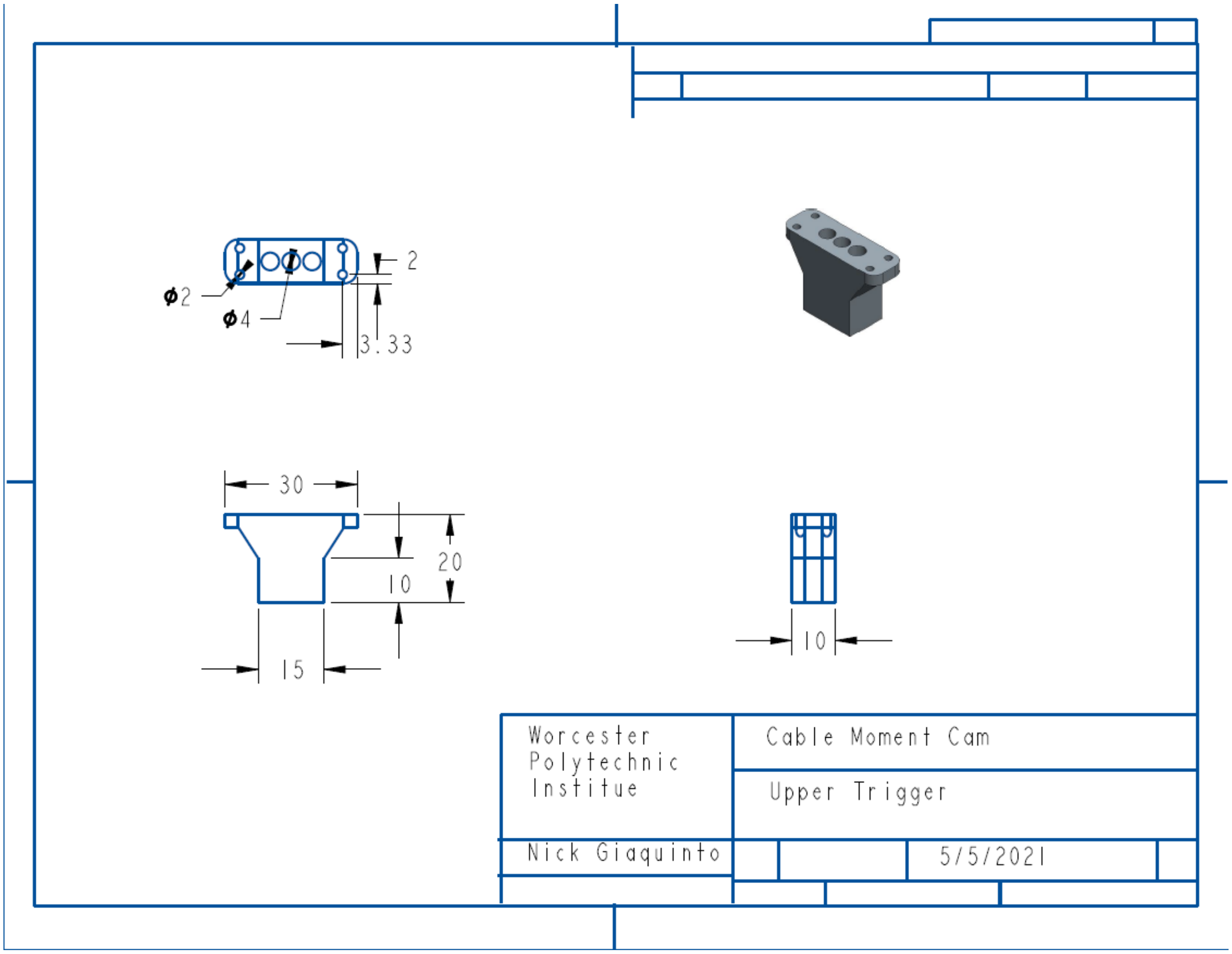
# Appendix D – Head Drawing



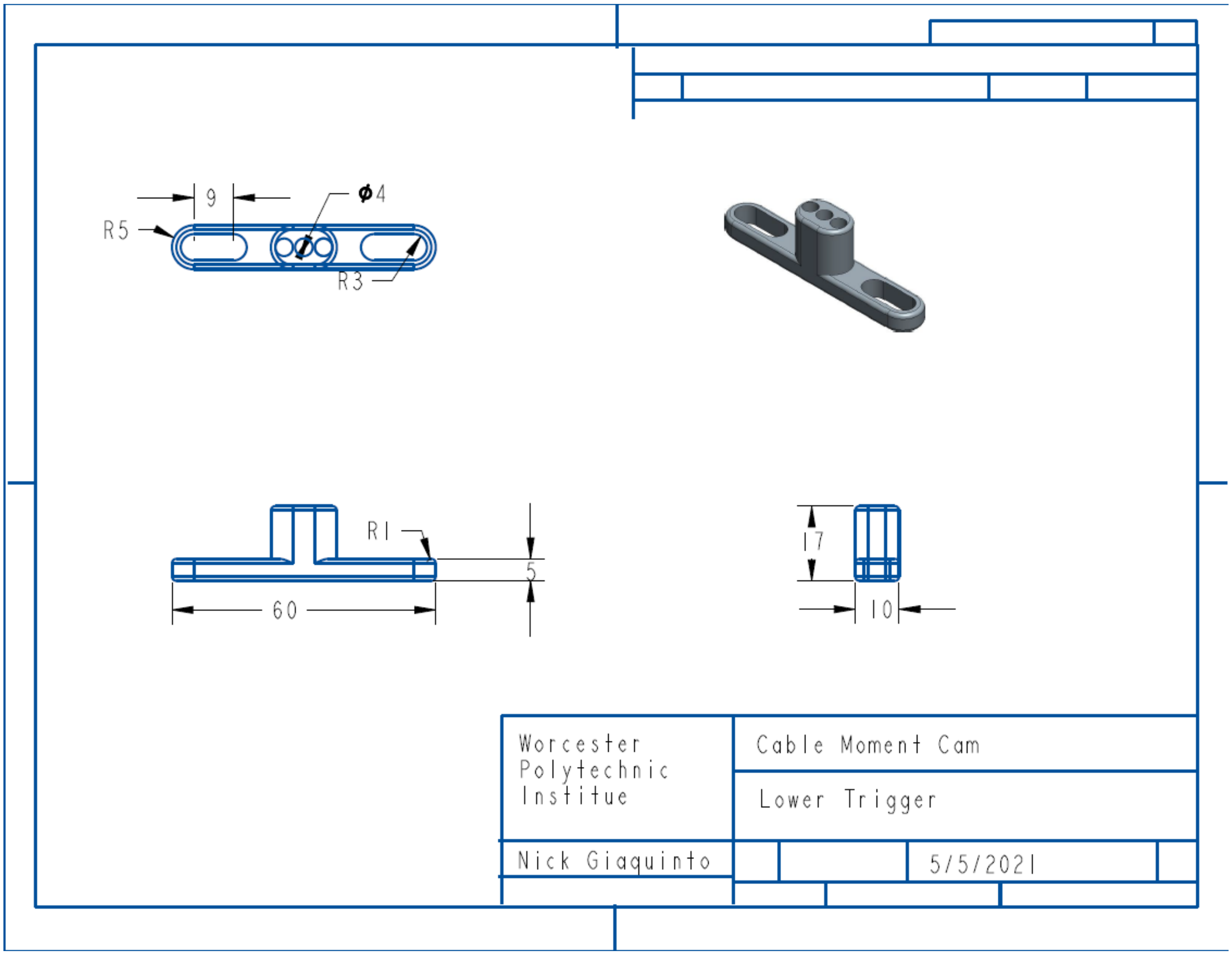
# Appendix E – Axle Drawing



# Appendix F – Upper Trigger Drawing



## Appendix G – Lower Trigger Drawing



# Appendix H – Thumb Loop Drawing