Spring Loaded Camming Device For Rock Climbing

Senior Design Project Report
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CONTENTS

ABSTRACT

The objective of this design project was to create a device for recreational rock climbing which would be capable of securing a climber to a crack in the cliff face. This device is intended to fit into a range of differently sized and shaped cracks and must be able to hold the force of a falling climber while simultaneously being as light as possible. Utilizing a spring-loaded camming device (cam) mechanism with two working axles, the manufactured cam acts similarly to existing market products including the Black Diamond Camalot and the Wild Country Friend product lines. However, it is unique in the design of its stem which utilizes Dyneema to minimize weight and specialized lobe design which maximizes the range of potential placements. Through product testing it was found that the cam was built with similar critical parameters to a Black Diamond Camalot #3. In a laboratory setting, this cam was capable of holding loads up to 10.4 kN, and in field testing, it was determined that the cam could be placed in cracks of various dimensions, satisfying the requirements for this project.

1. NOMENCLATURE

TABLE 1: NOMENCLATURE

Term	Meaning
Cam	Spring-Loaded Camming Device
Stem	The Part of the Cam that transfers the force from the rope to the lobes
Trad	Traditional Climbing
Traditional Climbing	Climbing while placing your own protection in a blank rock face
Protection	Any equipment that can secure a rope, and thus the climber, to rock
Placement	A secure hold of protection in a crack or rock feature
FEA	Finite Element Analysis

2. INTRODUCTION

The inspiration behind this project was to address the cost of current marketplace cams and their difficulty of use, which adds further barriers to entry to a sport already facing a lack of minority athletes. Recently, cams have started to gain even more traction as methods of protection, as more and more national parks started banning permanent metal anchors, such as drill-in bolts, forcing climbers to bring their own "traditional" equipment[6].

Rock climbing, a sport that requires a high degree of athleticism and mental resilience, carries a lot of risks, namely in falling and injuries. This risk necessitates reliable protection gear, with climbing cams being the popular choice among climbers. These devices, placed in cracks between rocks and other formations, act as a lifeline, anchoring climbers securely while climbing. Many existing climbing cams, however, are troubled with issues of limited adaptability to different crack sizes, excessive weight, and declining durability over time. These limitations can significantly impact a climber's safety and the cam's utility in diverse climbing environments. The motivation behind this project is to fix those problems, creating a climbing cam that surpasses the current safety and usability benchmarks, thereby enhancing the overall safety and experience of climbers.

Durability and long-term performance are also critical. A cam is designed to withstand repeated use without significant deformation. A high level of durability ensures that a cam maintains its functional shape and gripping ability over time, a vital attribute for ensuring climber safety throughout its lifespan.

Our objective in this project is creating a cam which can compete with current market options by:

1. Simplifying the design, cutting manufacturing costs and time, and in turn cutting the cost for the consumer,

2. Using interchangeable parts, simplifying assembly, and reducing waste, and,

3. Being more versatile, allowing for a greater operational range without sacrificing weight, ease of use, or cost.

2.1 Prior Art

There are two types of traditional climbing protection currently in use: passive and active[3]. Passive protection, as seen in Figure 1 is simple in that it has no moving parts, but lacks the versatility that active protection can provide.

FIGURE 1: PASSIVE CLIMBING PROTECTION

Active protection, on the other hand, utilizes moving parts to provide a larger range of secure placements. The most popular form of active protection is the cam, seen in Figure 2. Cams are composed of multiple lobes which can be forced to contract when the climber pulls a trigger in the stem. Once the cam is placed and the climber releases the trigger, the lobes of the cam will expand back to their original position, locking the cam into the rock.

Cams can be distinguished by several key features: the number of axles attached to the lobes and the complexity of each lobe's composition. One example of a cam with a single axle but multi-piece lobes is the Omega Pacific Link cam, seen in Figure 3. The Omega cam has larger range than other cams on the market but was difficult to extract from the cliff face in testing. Furthermore, it was prone to rapid, unplanned disassembly under torsional loads, largely becoming obsolete on the market [8].

Two axle cams, such as the Black Diamond Camalot C4 shown in Figure 4, provide a similarly great range by overlapping the swing path of the lobes, despite the relative limitation of a single piece lobe.

FIGURE 2: ACTIVE CLIMBING PROTECTION

FIGURE 3: OMEGA PACIFIC LINK CAM

While most differences in cam design surround the lobes, another design factor to consider is stem material. Dyneema, a novel composite material allowing for lighter, equally strong equipment, has only recently come on the market and to-date has not been utilized as a stem replacement [9].

3. REQUIREMENTS

Based on existing products made by Black Diamond and their properties as seen in Figure 5, it was determined that the following specifications would be needed for the cam as functional requirements and design criteria:

- Ideal 12 kN breaking strength at 50% and 100% lobe extension, 10 kN minimum

- Ideal functional range between 1.5-3", minimum range 2-3"

And the following design constraints would need to be followed:

- Less than 225g total weight, 275g maximum allowable

- Surviving repeated 6 kN falls

Further team-derived requirements were as follows:

- Less than 5 seconds average placement time

- 70% successful placement rate in appropriate cracks

Commercial products in this space also need to comply with CE and UIAA certifications[7]. However, this certification requires

FIGURE 4: BLACK DIAMOND C4 CAM

CAMALOT C4

Size #	Weight	Width Range Min./Max.	Operational Range	Holding Force	Passive Strength
.3	70 g (2.46 oz)	13.8-23.4 mm (0.54-0.92 in)	14.8-21.0 mm (0.582-0.827 in)	8 kN (1798 lbf)	8 kN (1798 lbf)
.4	78 g (2.73 oz)	15.5-26.7 mm (0.61-1.05 in)	16.6-23.8 mm (0.654-0.936 in)	9 kN (2023 lbf)	9 kN (2023 lbf)
.5	93 g (3.28 oz)	19.6-33.5 mm (0.77-1.32 in)	20.7-29.8 mm (0.815-1.172 in)		
.75	108 g (3.79 oz)	23.9-41.2 mm (0.94-1.62 in)	25.2-36.2 mm (0.992-1.424 in)		
1	124 g (4.37 oz)	30.2-52.1 mm (1.19-2.05 in)	32.3-45.7 mm (1.271-1.798 in)	12 kN (2698 lbf)	12 kN (2698 lbf)
2	140 g (4.94 oz)	37.2-64.9 mm (1.46-2.55 in)	40.6-57.2 mm (1.600-2.250 in)		
3	181 g (6.38 oz)	50.7-87.9 mm (2.00-3.46 in)	54.4-77.5 mm (2.140-3.050 in)		
4	258 g (9.09 oz)	66.0-114.7 mm (2.60-4.51 in)	70.9-102.4 mm (2.791-4.033 in)	14 kN (3147 lbf)	14 kN (3147 lbf)
5	348 g (12.28 oz)	85.4-148.5 mm (3.36-5.85 in)	91.9-132.7 mm (3.617-5.223 in)	14 kN (3147 lbf)	12 kN (2698 lbf)
6	530 g (1 lb 3 oz)	114.1-195.0 mm (4.50-7.68 in)	128.0-175.4 mm (5.038-6.906 in)		
7	709 g (1 lb 9 oz)	150-253.3 mm (5.9-9.97 in)	160.3-227.6 mm (6.31-8.96 in)	8 kN (1798 lbf)	8 kN (1798 lbf)
8	965 g (2 lbs 2 oz)	193-321.2 mm (7.6-12.65 in)	205.8-289.2 mm (8.1-11.39 in)	5 kN (1,124 lbf)	5 kN (1,124 lbf)

FIGURE 5: BLACK DIAMOND CAMALOT C4 PARAMETERS [1]

destructive testing to ensure that the cam is capable of holding 5 kN at 25 and 75% extension of the lobes, which is impossible given minimal materials and timescale of this project.

4. PRODUCT DESIGN

The manufactured cam is a two lobe design, similar to the Black Diamond Camalot series but utilizing Dyneema to reduce the weight of the stem as seen in Figures 6 and 11. The base is designed to be easily machinable and connects the Dyneema stem to the axles using a third sling axle part shown in Appendix E. The holes in the lobe are meant to both reduce the weight of the cam and to allow for easier machining through the use of a jig.

Several additional design concepts were also considered and are further discussed in Section 4.2.

4.1 Theoretical Background

The primary design concern for this cam is the failure of parts due to mechanical loading. Most climbing falls generate between 4 and 6 kN of force, proving a substantial safety factor given that

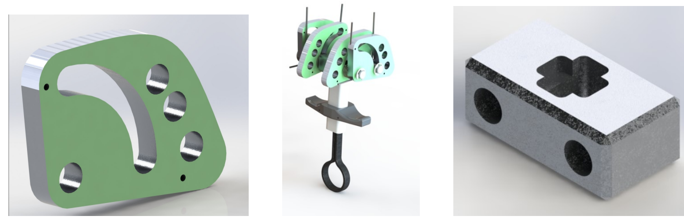

FIGURE 6: CAD RENDERINGS OF FINAL DESIGN

protection is designed to break at 12 kN. In order to ensure that the cam breaks at these strengths, the following principles were used when designing this cam:

Given that Stress=Force/Area[2]:

$$\sigma = \frac{F}{A} \tag{1}$$

Converting the 12 kN value to imperial units, for machining purposes, yields 2697.7 lbf applied to the cam. The yield strength, σ_y, of 6061 Al, the material chosen for the cam due to its light weight and machinability, is 35000 psi meaning that based off of the calculation in Equation 2 the minimum cross sectional area of any part of the cam must be 0.77 in^2.

$$\sigma_y = 35000 \text{ psi} = \frac{F}{A} = \frac{2697.7 \text{ lbf}}{A} \tag{2}$$

Based off these calculations for any circular cross section, a minimum diameter of 5/16" is required. For a rectangular cross section, if both sides have minimum side lengths of 5/16", it is safe to assume that the part will not break. When determining hole placement, the standard convention of the center of the hole being one diameter from the edge was implemented.

4.2 Concept Development

The functional diagram of the cam is shown in Figure 7. Based off prior art, the ergonomics of the trigger were chosen to be similar to other designs, requiring little modification. This also simplifies the learning curve for climbers utilizing this piece of gear. For each part of the cam, multiple design options were considered, except for the springs, for which torsion springs remain the only realistic option.

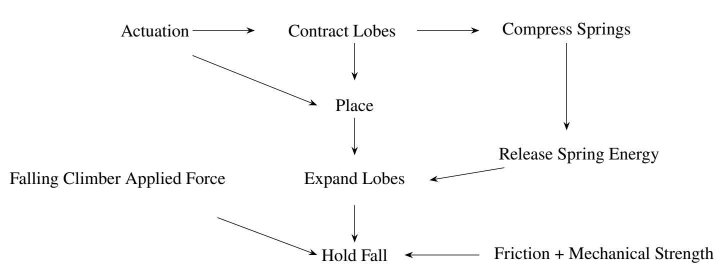

FIGURE 7: FUNCTIONAL DIAGRAM

4.2.1 Lobe Design. There were multiple options considered for the lobe design as seen in Table 2. The "Single Piece Two Axle" design was chosen, as this design provides the greatest balance between range, mechanical simplicity, and maneuverability. Existing competitors also primarily utilize this design due to these advantages.

TABLE 2: LOBE DESIGN OPTIONS

Design Choice	Pros	Cons
Single Piece Single Axle	Simplest	Limited range
Single Piece Two Axle	Easy to machine	Improved range
Multi Piece Single Axle	Improved Range	More failure points
Multi Piece Multi Axle	Biggest Range	Hard to build

Once this geometry was selected, multiple possibilities were also considered for the geometry of the lobe. As seen in Appendix A, designs were considered where sections of the lobe were thinner than the areas around the axles and the edges. This design was not pursued as it would require more complex machining without substantial weight reductions.

4.2.2 Stem Design. The stem of the cam absorbs the entire load applied and thus must be the strongest part. Additionally, since it transfers the load from a falling climber to the rest of the cam, which is located deep within a crack, it is necessary for it to maintain its tensile strength as it bends around a sharp corner. Due to these requirements of high tensile strength and flexibility, two options were considered for the stem: a steel cable loop and Dyneema loop. The Dyneema was chosen due to its significantly higher strength to weight ratio, as well as its increased flexibility. The one advantage that the steel loop does maintain over the Dyneema is better resistance to high temperatures, but that temperature range is not typically encountered in a rock climbing environment.

4.2.3 Lobe Axle. The axle(s) which connects the lobes to the base of the cam is a critical component as it attaches the moving parts of the cam to parts where the load is applied. In order to efficiently perform this task, the axle must be strong and stiff. Several options were considered for this part, as seen in Table 3.

TABLE 3: LOBE AXLE DESIGN OPTIONS

Design Choice	Pros	Cons
Integrated	Lowest part count	Hard to machine
Machined Al	Easier to Machine	Less stiff than steel
Clevis Pin	Simple procurement	Heavy

The clevis pin was chosen due to the fact that it was an existing McMaster-Carr part and thus required no in-house manufacturing. The steel material also provides a better surface for the lobes to pivot against. The only drawbacks with this choice are that it requires the sling axles to be a predetermined length and that steel is substantially heavier than the aluminum that would be used on an in-house axle.

4.2.4 Sling Axle Geometry/Retention. For the sling axle, which connects the stem of the cam to the base, several options were considered. The first of these options was a "dumbbell" shaped sling axle with a flat-bottomed groove in the base to accommodate it. This design has the advantage of providing the greatest mechanical strength, but is extremely difficult to manufacture given the complex geometry. Similarly, making the retention area for the axle on the base rounded would have drastically increased the complexity of this part for machining. Thus, the simplest design to manufacture is a flat cutout in the base, accompanied by a corresponding flat face in the sling axle.

4.2.5 Base Corners. In initial renderings of the design, the corners of the base were rounded. This provides maximal weight savings, as well as superior aesthetics. The final design is square as this facilitates rapid machining, as less material has to be removed.

4.2.6 Machining Material. Several metals were considered for the machined parts: aluminum, steel, and titanium. Titanium was eliminated due to the complexities of working with the metal, as well as the significant cost of raw stock. Aluminum was chosen over steel due to its superior strength to weight ratio in an application where weight is prioritized.

Aluminum stands out as the optimal material choice for a climbing anchor application due to several key factors. Firstly, aluminum offers a remarkable strength-to-weight ratio, making it lightweight yet incredibly durable. This characteristic is paramount for climbing, where minimizing weight without compromising strength is crucial for user safety and convenience during ascents.

Additionally, aluminum exhibits excellent corrosion resistance, particularly when treated with protective coatings or anodized. This resistance is essential, as anchors are frequently exposed to harsh outdoor environments, including moisture, humidity, and varying temperatures. The ability of aluminum to withstand these conditions ensures the longevity and reliability of our parts over time, reducing the need for frequent replacements and contributing to overall sustainability.

Moreover, aluminum is easily machinable, allowing for our design to be manufactured easily with minimal obstacles provided by the material.

As mentioned in Section 4.4, aluminum is inherently recyclable, with a high scrap value and minimal loss of properties during the recycling process. This potential to be recycled aligns with this project's sustainability goals, as it reduces the environmental impact of production and promotes a closed-loop system for materials.

4.3 Design Detail

Based on the theory demonstrated in Section 4.1, the final design was constructed such that every cross section of the design inside of the load bearing areas had a minimum size of 0.77 in^2. Once the general shape of the design was determined, this principle was used to fine-tune dimensions in construction.

Further simulations were done using both ANSYS and Solidworks Simulation software in order to determine the stresses that the cam would experience under higher loads. One challenge with these simulations is the fact that it is extremely difficult to model the stresses that the lobe would experience in a real-world scenario. A falling climber results in uneven friction between the lobes of the cam and the rock. Swinging can also result in rotational forces which are difficult to model. The manufactured cam, in its full complexity, includes over 40 connections and contact points, mirroring the intricate design of an actual climbing cam. However, given this complexity, the model introduces a multitude of potential errors and complexities in the FEA. Therefore, in order to optimize understanding of potential stressors, two simulations were performed:

1. A static simulation with the lobes bonded to the axles in their widest orientation, with the outermost corners of the lobes fixed in place, and a 10 kN load on the sling axle, and,

2. A static simulation with the lobe axles fixed in place and a 10 kN load on the sling axle.

This approach allows for a high resolution simulation around the engineered point of failure (the sling axle), while simultaneously allowing for an approximation of the forces that the lobes will experience.

4.3.1 Bonded Lobe Simulation. This simulation was performed by suppressing all of the components in the design other than the base, the sling axle, the clevis pins (lobe axles), and the lobes. Using bonded connections for each of the parts, the lobes were fixed in place at their widest position (all the way open) by fixing the face of the outermost corner in 3D space. Next, an external load of 10 kN was placed on the sling axle, in a downward direction. A mesh was created and the simulation was run. As seen in Figure 8 The Von Mises Stress in the cam reached a maximum of 29,690 psi, below the yield strength of 35,000 psi. This maximal stress was also on the sling axle. The deformation of the cam, as seen in 9 was also greatest in the sling axle.

4.3.2 Base Structural Simulation. This simulation was performed on a further simplified model of the cam: the only parts tested were the sling axle, the base, and the lobe axles. The lobe axles were fixed and, with all of the connections once again bonded, the sling axle was loaded with 10 kN. As seen in Figure 10, this simulation provides an extremely different value for the Von Mises stress, despite theoretically similar boundary conditions. This simulation does however demonstrate that the sling axle is expected to fail in the same manner and location, which provides greater confidence in the first simulation, which matches the hand calculations far more closely.

4.4 Design for Sustainability

One of the significant factors considered in the design of the cam was sustainability, with the objective of minimizing the environmental impact. This design emphasizes simplicity and minimalism, facilitating a streamlined manufacturing process which consumes less energy and creates minimal solid waste. This was done through the use of 3D printing, which minimizes plastic waste, as well as optimized design which reduces the amount of wasted metal stock on machined parts. By optimizing for an easily machinable design which uses standard stock sizes, both material and energy use is reduced, optimizing production efficiency. This approach translated into significant savings in material costs, production expenses, and build time. Moreover, the design featured interchangeable parts, extending the lifespan of the cam through the replacement of individual damaged components. This further minimized solid waste generation, which is a critical component of sustainability. Another critical component of sustainability is the recycling of waste material. The NYU Tandon Makerspace was pivotal to the fulfillment of this goal enforcing policies such as the recycling of 3D printed materials and metal chips. Through these strategies this project, demonstrated a commitment to sustainability in the climbing industry.

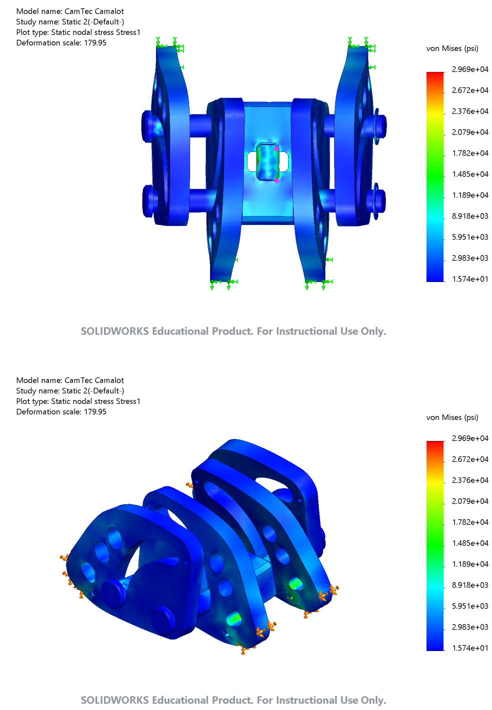

FIGURE 8: VON MISES STRESS IN THE CAM IN SIMULATION 1

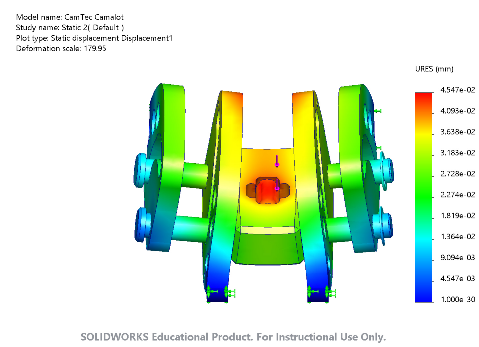

FIGURE 9: DISPLACEMENT OF THE CAM IN SIMULATION 1

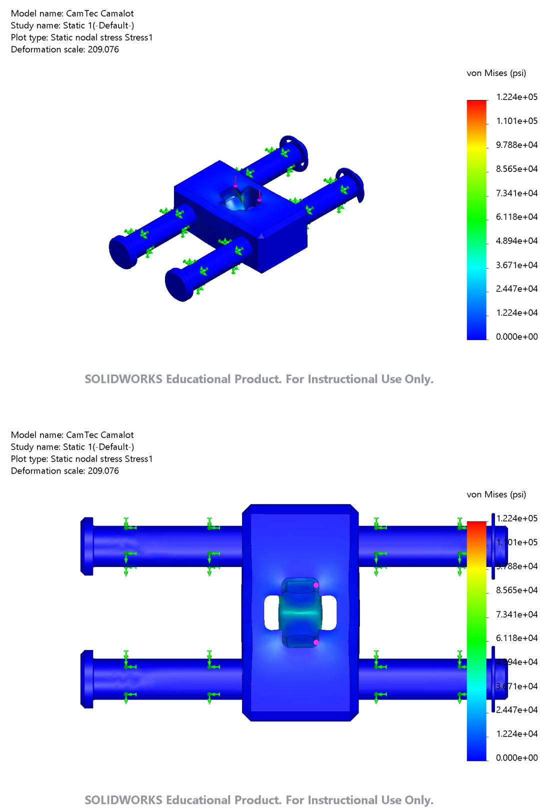

FIGURE 10: VON MISES STRESS IN THE CAM IN SIMULATION 2

FIGURE 11: FINAL ASSEMBLY

5. FABRICATION AND ASSEMBLY

The final assembly can be seen in Figure 11, the lobes are shown in each of the stages of extension, from widest to narrowest.

5.1 Cost Analysis

The bill of materials for the cam is as follows:

TABLE 4: BILL OF MATERIALS

Part	Quantity	Cost
Base (machined)	1	2.98
Sling Axle (machined)	1	0.42
Steel Washers	2	1.5
Lobe (machined)	4	3.28
Dyneema Sling	1	15.11
Torsion Spring	4	6.56
Clevis Pin (Lobe Axle)	2	19.90
Trigger Sleeve	1	0 (in-house)
Actuation Trigger	1	0 (in-house)
Structural Adhesive	10 (g)	2.10
Steel Wire	8 (in)	0.50
PTFE washers	8	6.10
Total	1	**58.45**

The parts labeled "in-house" are produced through means of 3D Printers that are provided free of charge through the NYU Tandon Makerspace. Their integration into the design offers numerous advantages which align with both performance, production, and sustainability goals. Utilizing 3D printing for the actuation trigger and the trigger sleeve allows for rapid and efficient manufacturing of high precision, complex, ergonomic parts without the obstacles that injection molding or machining create. This method enables the creation of intricate shapes and structures that would be difficult or impossible to achieve using traditional manufacturing methods. Additionally, 3D printing reduces material waste by only using the material needed for the final part, contributing to sustainability efforts and lowering production costs. Furthermore, the rapid prototyping and iteration capabilities facilitate faster development cycles and more efficient testing of new part designs, leading to continuous improvement and innovation in product design. With on-demand manufacturing and a growing range of available materials, including lightweight polymers and advanced metal alloys, 3D printing enables the creation of safer, more efficient, and more sustainable gear for climbers.

When transitioning a prototype design to production, material costs can be significantly impacted. The quantity of materials required for mass production is typically much higher than for prototyping. This would enable us to obtain bulk discounts on raw materials, which can lead to reduced per-unit material costs. Furthermore, advancements in manufacturing technologies or processes may enable more efficient utilization of materials, further reducing costs when our design is brought to mass-production. Many of the 3D parts can also be injection molded, which reduces costs significantly on large production runs after a large upfront mold cost. A final consideration for moving this design to production is the cost associated with testing and certification, which involves costly equipment, time, and the sacrificing of multiple production units for destructive testing.

5.2 Fabrication

The cam is made up of 10 distinct parts as seen in the Drawings in Appendix E. The parts that are machined include all 4 lobes, the base, and the sling axle. The trigger sleeve and actuation trigger are both 3D Printed. The rest of the parts were purchased from McMaster Carr. The Dyneema sling was purchased from a sporting goods retailer.

The cam was assembled by threading the sling axle through the Dyneema Sling and inserting both into the Base such that the Sling Axle Slots into the Base and the two flat faces are Touching.

Next, the other end of the Dyneema Sling was threaded through the Trigger Sleeve. These Parts were epoxied together such that the trigger sleeve was rigidly attached to the Base and the sling axle could not fall out, thus locking the Sling in place.

The rest of the assembly was performed by threading the remaining components onto the Clevis pins such that the springs provided tension on the lobes toward their naturally widest positions. The washers were used to reduce wear and friction in the joints. The order of this stacking can be seen in Figure 12 and the assembly drawing in Appendix E.

Torsion springs were connected to each of the lobes by bending the lever arm and threading it through the hole in the lobe. The coil was placed such that the lobe axles threaded through the middle of the springs, and the opposite lever arm was placed against the other lobe axle, thus tensioning the lobes to their widest position. The reliability of this spring loaded mechanism is critical to the performance of the cam. These bent springs can be seen in Figure 12.

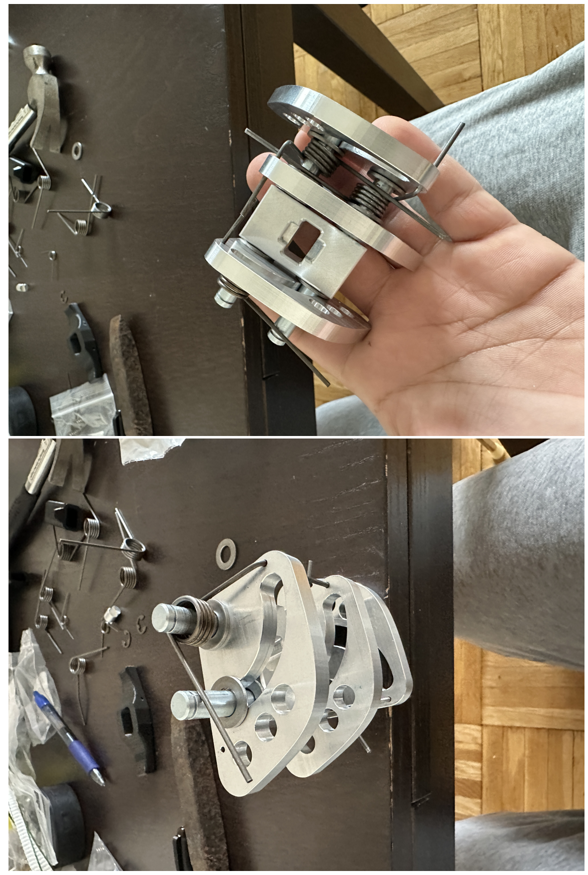

FIGURE 12: FABRICATION OF THE CAM

6. TESTING AND EVALUATION

There were two distinct types of testing performed on the cam. Tests were performed in a laboratory environment in order to determine numerical values for significant properties of the cam including its weight, trigger actuation force, minimum passive breaking strength, and active frictional holding ability. Field testing was also performed on the cam in order to determine its versatility.

- Lab Testing
- Field Testing

6.1 Lab Testing

Lab testing was performed on the cam in order to determine several physical characteristics of the cam such as weight and trigger actuation force, as well as several mechanical properties including the passive breaking strength and the ability of the cam to hold a person in an active orientation. An extensive walk-through of the following test procedures can be found in the appendix D

6.1.1 Physical Parameters. Testing was performed on the cam in order to determine the mass and the trigger actuation force. These were found to be 260 g and 14.7 N respectively satisfying the requirements.

6.1.2 Passive Breaking Strength. Using an Instron tensile testing machine, the base, sling axle, and sling were tested in tension. This test was designed to validate the weakest part of the structure of the cam, destructively, in order to determine how much force is required to break the cam. The fixturing of the cam, as seen in Figure 13 was used to gradually pull on the cam at an expansion rate of 6 mm/min until failure, which occurred the shoulders of the sling axle as shown in Figure 13 at an applied force of 10.4 kN, passing the threshold established for this project.

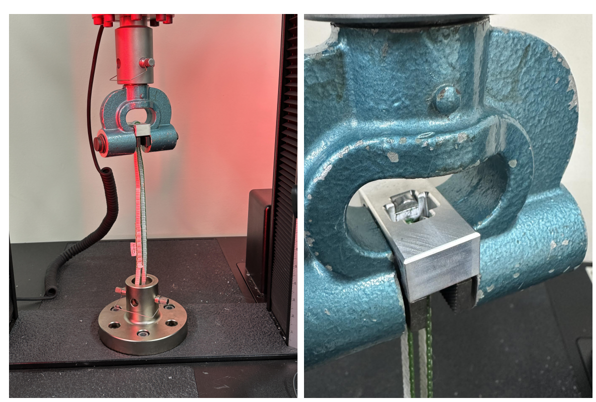

FIGURE 13: TENSILE TESTING EXPERIMENTAL SETUP AND RESULT

6.1.3 Parallel Plate Testing. In order to determine whether or not the cam could function purely as a frictional anchor, a structure was constructed as shown in Figure 14. At the top of this frame is a crack, approximately 2.5" wide lined on both sides by a cinder block. The cam was placed in this crack and was loaded with the body weight of a person using a climbing harness. This test was considered successful due to the fact that the cam remained in place and the climber did not fall.

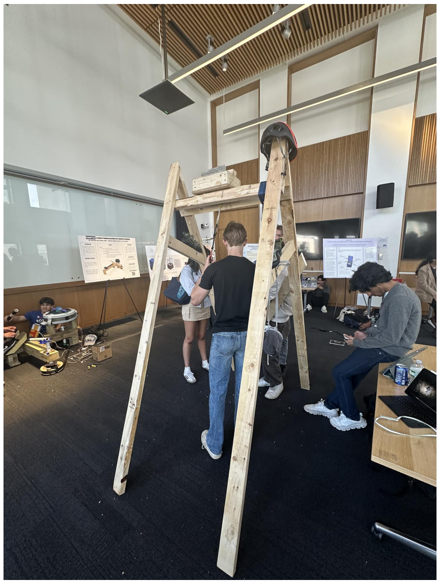

FIGURE 14: PARALLEL PLATE TESTING EXPERIMENTAL SETUP

6.2 Field testing

Field testing was performed on the cam in order to determine how well the cam would fare in a real climbing environment. Rocks are extremely nonuniform, and thus it is impossible to replicate the conditions that a cam will experience in a laboratory setting. These tests are critical in determining whether or not the cam is useful in a diverse range of placements as well as determining whether or not it is possible to remove the cam from the rock after experiencing loading.

6.2.1 Placement time, range, and security. In order to determine whether or not is easy to place the cam and to subsequently evaluate the cam's security in a placement, field testing was performed in New York's Central Park. The test procedure can be found in the testing plans in the appendix D. If the cam successfully completes this procedure, it can be determined that the cam is sufficiently simple to place in natural rock features, that it has sufficient practical range to be useful in diverse placements, and that it is able to be removed from these placements. Successfully demonstrating these properties indicates that the cam is capable of being used by climbers in the field. Images from this testing can be seen in Appendix B.

In performing these tests, it was found that the cam could successfully be placed in fewer than 5 seconds in 8/10 distinct placements, indicating both that the cam is usable and that the team-derived requirements were met. This further indicates that the cam was secure in multiple different placements.

6.2.2 Future Testing, Yosemite, CA. The final field test, which will be performed approximately two weeks after project submission, involves climbing Reed's Pinnacle by the direct route[5], placing two purchased cams into the crack adjacent to one another, placing the built cam approximately a foot higher in the crack, climbing approximately five feet higher, and intentionally falling.

7. CONCLUSION AND FUTURE WORK

As indicated by both the laboratory and field testing results, the cam constructed can be successfully used in trad climbing. Each of the design criteria was met, and the cam successfully held the weight of a climber on a natural rock face. There were, however, several design modifications that would need to be made in order to make this a viable commercial product.

The principal modification is the modification of the trigger wire attachment point to the lobe. Changing this location to be higher on the lobes would lead to superior power transmission and subsequently improve the ease with which the lobes can be contracted. Additionally, the trigger sleeve would need to be modified with a new material which is more flexible than the ABS sleeves used in earlier prototypes, which broke in horizontal placements, yet stiffer than the TPU sleeves used on later prototypes, which experienced buckling at maximal trigger pulling. However, this non-structural part is not critical to the survival of the cam.

Additional design modifications that could be made to further reduce the weight of the cam, at the cost of machinability, would include rounding the corners of the base, as seen in the design alternatives in Appendix A, and removing more material from the lobes, as seen in much of the prior art shown in Section 2.1. This optimization could be performed to reduce the amount of metal in these parts while still maintaining the current designed point of failure in the sling axle, maximally reducing the weight of the cam.

Further changes, which would only be possible with larger production numbers, include using customized torsion springs to improve the torque curve of the actuation trigger as well as reducing the axial distance between the lobes, allowing for both a weight reduction and a narrower footprint. Access to improved machinery could allow for the use of titanium instead of steel to further reduce the weight of the lobe axles.

Finally, additional avenues that could be pursued would include building cams with different numbers of lobes as well as cams of different sizes.

8. ACKNOWLEDGEMENTS

We would like to thank Oleg, the NYU Tandon machinist, for all of his help with manufacturing and machinibiliy studies. We would also like to thank Maria Olifer (NYU Wagner '24) for her assistance with climbing expertise and editing. Finally we would like to thank Logan Calder (NYU Tish '23) for his assistance with locations for field testing and his willingness to be the first person outside the group to fall on the cam.

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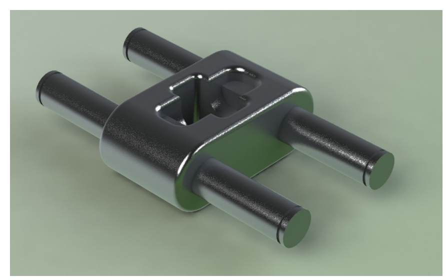
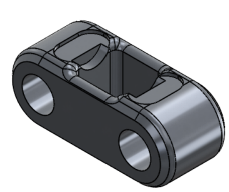
APPENDIX A. DESIGN ALTERNATIVES

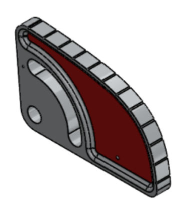
TABLE 5: DESIGN ALTERNATIVES TABLE

Feature	Design Choice 1	Design Choice 2	Design Choice 3	Design Choice 4
Lobe	Single Piece Single Axle	*Single Piece Two Axle*	Multi Piece Single Axle	Multi Piece Two Axle
Stem	Steel Cable	*Dyneema*		
Lobe Axle	Separately Machined	Integrated	*Clevis Pin*	
Sling Axle Retention	Rounded Bottom	*Flat Bottom*	Dumbbell	
Base Corners	Rounded	*Square*		
Part Material	Steel	*Aluminum*	Titanium	

Italisized selections indicate choices used in the final design.







APPENDIX B. FIELD TESTING

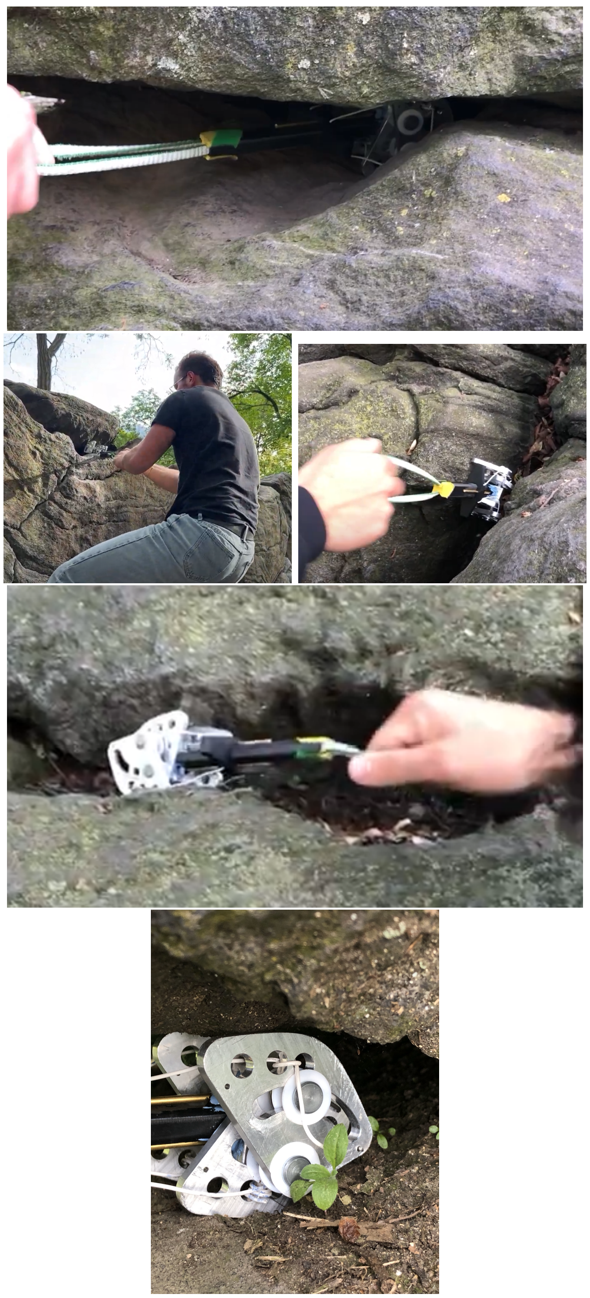


FIGURE 15: FIELD TESTING

APPENDIX C. IMPACT MATRIX

Issue	**Raw Materials**	**Suppliers**	**Production**	**Distribution**	**Use**
Material Use	Aluminum mined as Bauxite, mined in jungles causing deforestation.	Produce carbon emissions through transportation of Bauxite.	Chemical pollution from extraction of aluminum.	Packaging leaves paper and plastic waste, transportation adds to carbon emissions.	Scraps and leftovers from manufacturing not being recycled.
Energy Use	17,000 kWh to produce 1 ton of aluminum.	Fossil fuels used for transportation.	Energy Consumption, based on NYU energy consumption policies.	Packaging requires energy consumption and delivery consumes fossil fuels.	Device requires human energy
Solid Waste	Rubble and leftovers from deforestation.	Unethically sourced materials from suppliers	Scraps from creating parts going unrecycled. Adds to landfill overuse	Packaging leaves paper and plastic waste, delivering adds to carbon emissions.	Broken pieces cannot be reused for safery reasons
Social Liability	Large scale procurement impacts businesses and communities.	Exploit populations for work and resources.	exploits local communities and workers	n/a	Misuse can damage property and ecology

APPENDIX D. TESTING PLANS

D.1 Lab Testing

D.1.1 Physical Parameters. The test to determine the mass of the cam is done by placing the cam on a scale. Further instructions for this test can be found at this source [4].

The test to determine the trigger actuation force was done as follows:

1. Fix a scale in place on a vice such that the plate of the scale is facing vertically upwards.
2. Attach the actuation trigger to the scale using a material that is rigid in tension (duct tape was used).
3. Lift the cam by the base until the entire mass of the cam is supported by the base, but none of the lobes are being compressed.
4. Zero the scale.
5. Pull on the base of the cam until the lobes are fully retracted. This will place tension on the duct tape and trigger.
6. The value that the scale reads multiplied by $g = 9.81\text{m/s}^2$ is the actuation force.

D.1.2 Passive Breaking Strength. This test was used to test the minimum passive breaking strength of the cam.

1. Fixture the base, sling axle, and Dyneema sling as shown in Figure 13 in an Instron tensile testing machine.
2. Pretension the system with a load of 50 N.
3. Begin the test by expanding the fixture at a rate of 6 mm/min
4. Record the maximum force that the apparatus can hold before failure.

A passing score in this test represents a force greater than 10kN.

D.1.3 Parallel Plate Testing.

1. Create an A frame structure as shown in Figure 14 with a 2.5" wide crack lined by cinder blocks in the top cross bar.
2. Place the cam into the crack.
3. Weight the cam with the force of a climber sitting in a harness.
4. Remove the load from the cam.
5. Remove the cam from the crack.

This test is considered successful if the cam holds the load without slipping out or sustaining any physical damage.

D.2 Field Testing

1. Ensure that the device is functioning fully
2. Locate a crack in a rock that is within the approximate range of the cam (2-3.5" wide)
3. Place the cam while timing the placement
4. Pull on the cam to ensure that it is seated correctly
5. Place the cam under the load of one person hanging
6. Remove the load from the cam
7. Remove the cam from the crack
8. Repeat this procedure for as many distinctly shaped cracks as possible

The test is considered successful if the cam is able to be placed in under 5 seconds, capable of holding the load, and able to be removed in under 5 seconds. The minimum passing threshold for this test is 70% of all trials being successful.

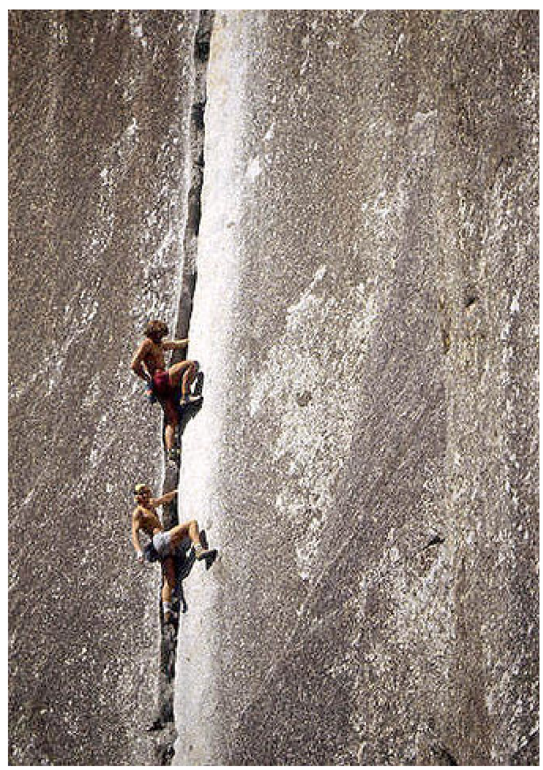
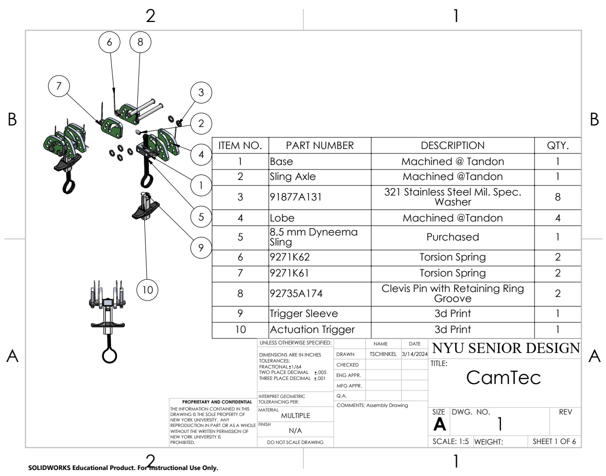
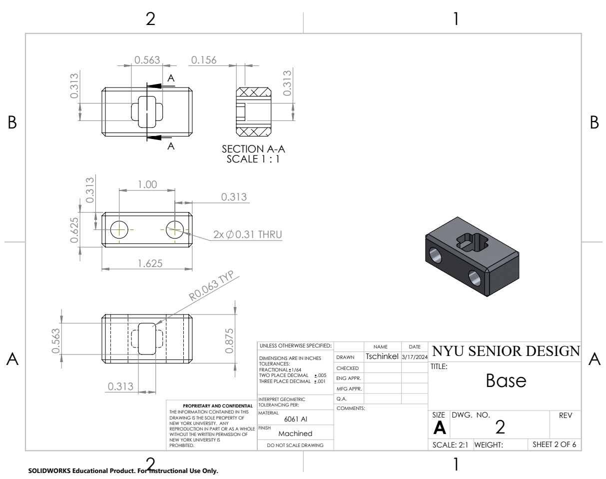


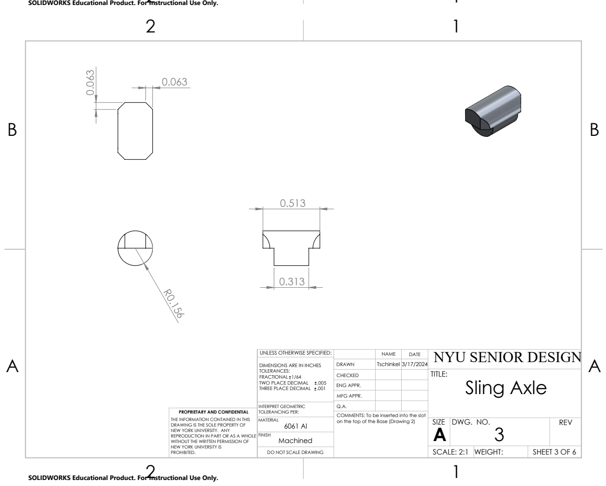
FIGURE 16: YOSEMITE FIELD TESTING ROUTE

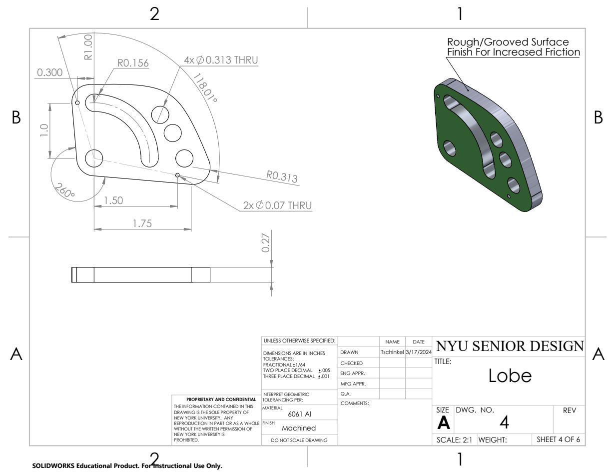
APPENDIX E. ENGINEERING DRAWINGS

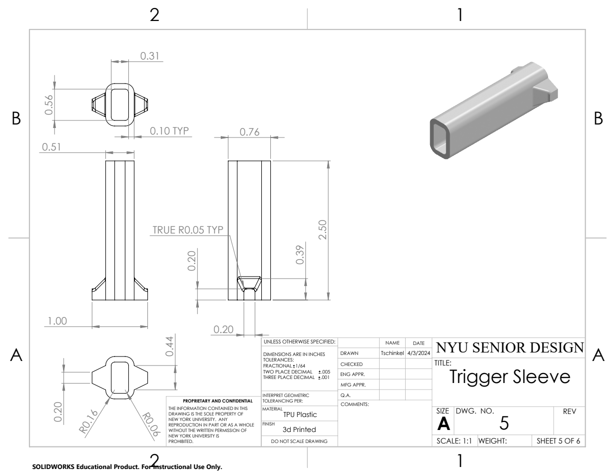


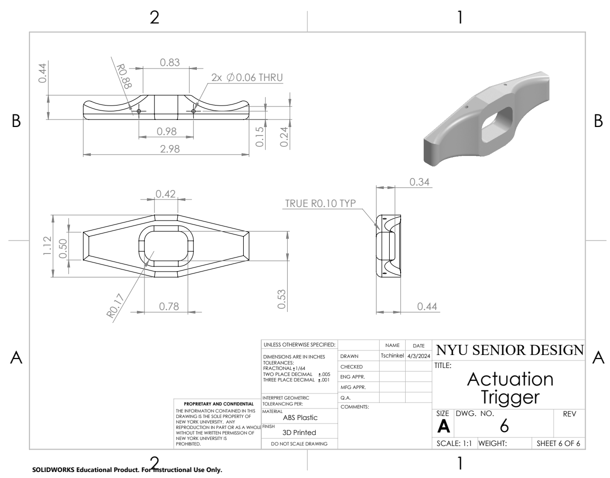
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base	Machined @ Tandon	1
2	Sling Axle	Machined @Tandon	1
3	91877A131	321 Stainless Steel Mil. Spec. Washer	8
4	Lobe	Machined @Tandon	4
5	8.5 mm Dyneema Sling	Purchased	1
6	9271K62	Torsion Spring	2
7	9271K61	Torsion Spring	2
8	92735A174	Clevis Pin with Retaining Ring Groove	2
9	Trigger Sleeve	3d Print	1
10	Actuation Trigger	3d Print	1

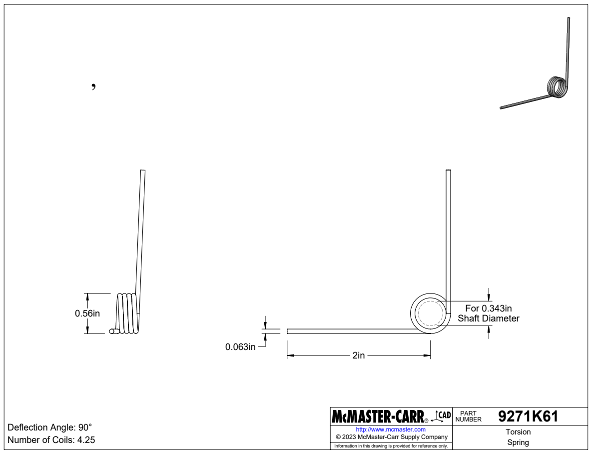


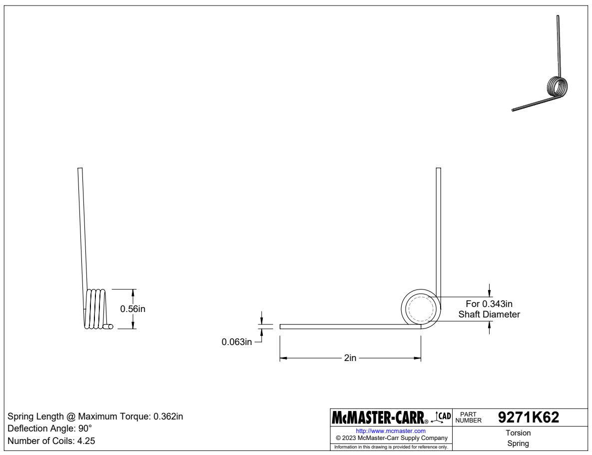


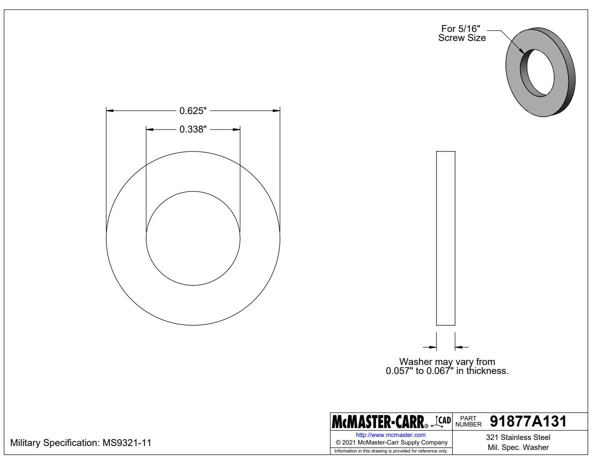


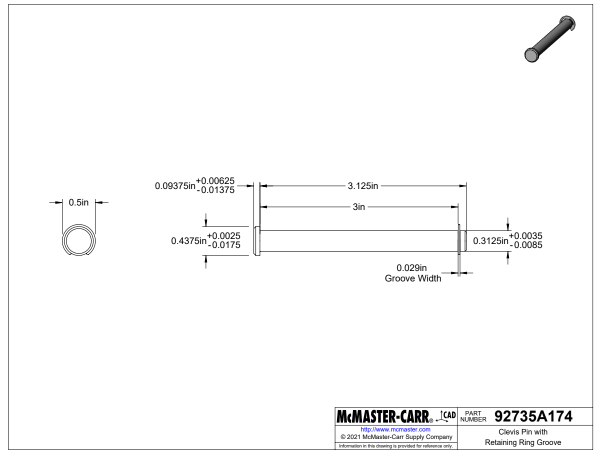





0.56in
For 0.343in
Shaft Diameter
0.063in
2in
Deflection Angle: 90°
Number of Coils: 4.25
McMASTER-CARR
PART NUMBER
9271K61
http://www.mcmaster.com
© 2023 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Torsion
Spring


0.56in
For 0.343in
Shaft Diameter
0.063in
2in
Spring Length @ Maximum Torque: 0.362in
Deflection Angle: 90°
Number of Coils: 4.25
McMASTER-CARR
PART NUMBER
9271K62
http://www.mcmaster.com
© 2023 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Torsion
Spring


For 5/16"
Screw Size
0.625"
0.338"
Washer may vary from
0.057" to 0.067" in thickness.
Military Specification: MS9321-11
McMASTER-CARR
PART NUMBER
91877A131
http://www.mcmaster.com
© 2021 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
321 Stainless Steel
Mil. Spec. Washer


0.5in
0.09375in +0.00625 -0.01375
3.125in
3in
0.4375in +0.0025 -0.0175
0.3125in +0.0035 -0.0085
0.029in
Groove Width
McMASTER-CARR
PART NUMBER
92735A174
http://www.mcmaster.com
© 2021 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Clevis Pin with
Retaining Ring Groove