Tensile Strength Assessment of Rock Climbing Protective Camming Device

MECH 306 Lab Section L2B, Team #35

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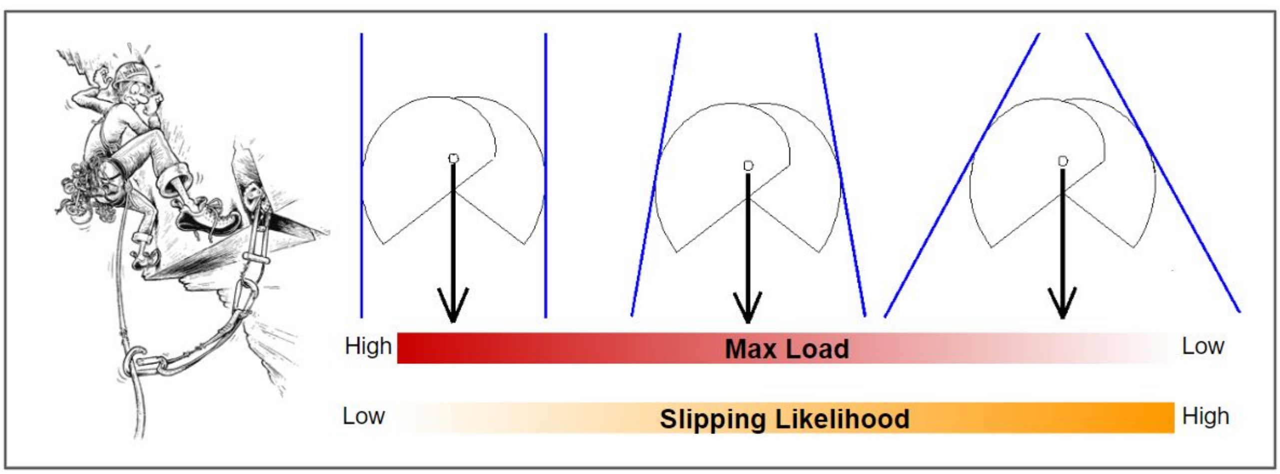
ABSTRACT

Our experiment was an analysis of the performance and reliability of spring-loaded camming devices used for rock climbing or mountaineering purposes. The specific objective of our experiment was to determine the maximum holding capacity of a spring-loaded camming device placed into an obtuse-angled rock fracture, as a function of the crack angle. To test this, we built an aluminum jig that the cam could be placed inside, and varied the crack angle from 9.5 to 21.5 degrees. A steadily increasing load was then applied until the cam released from the jig. We recorded the applied force versus the overall deflection from the original position. From our experiment, we were able to determine a relationship between the maximum load of the cam and the angle of the crack:

$$P = 7030 - 581\theta + 13\theta^2$$

As the crack angle became larger, We found that the maximum cam strength decreased proportional to the square of the angle. Therefore, cams placed in large-angle cracks provide significantly worse protection for climbers and may be unable to arrest a fall. Our experiment also produced an unforeseen result that we were able to analyze; the camming device tended to slide down the crack slightly, then re-engage and continue to bear an equivalent or greater load. We found that in large-angle cracks, the camming device was more likely to slip in small amounts at low loads and would start to majorly slip at values 10-20% less than the maximum load. Conversely, in small-angle cracks the cams tended to remain stationary, until they reached their maximum load when they ejected from the crack.



1.0 INTRODUCTION

In outdoor rock climbing, climbers use protection equipment (referred to as “protection”) to secure their rope to the rock faces. A climber places a piece of protection in a natural formation on the rock, clips their rope to the protection, and continues to climb above it. If the climber were to fall, their fall is arrested by the protection they have placed.

One of the most common forms of protection is a spring-loaded camming device, or “cam” for short. Cams come in a variety of different sizes and shapes and they are typically placed in cracks or other parallel features. A climber puts his life in the hands of these devices. It is extremely rare for a crack to have ideal geometry for maximum cam strength; therefore, the purpose of this experiment is to determine the reliability of a cam in features of varying geometry. More specifically, we focus on how the cam responds to variations in crack angle. Our experiment also provides some insight on interactions between the cam and the crack, such as the cams ability to slip slightly and re-engage or how wear of the crack surface affects the strength on repeat trials. Readers who partake in rock climbing would be interested in our work since this experiment provides some knowledge of effective cam placements.

The camming device we are using in this experiment is a size 0.75 Camalot C4 from Black Diamond [1], which is a very popular type of cam. This cam size was chosen because it is the smallest cam size with a maximum rated load of 14kN, and a smaller cam minimizes the cost of our jig.

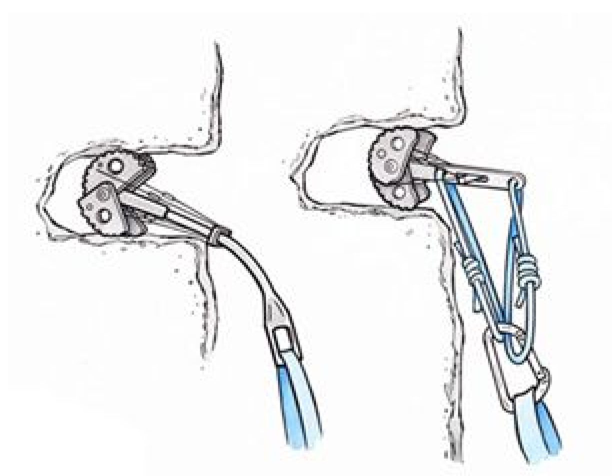


Figure 1: Camming Device Working Mechanism

2.0 METHODS

The climbing cam, pictured in Figure 2, operates by leveraging the load force (T) of the climber into the walls of the crack. The large normal force on the crack provides enough friction on the cam for it to remain in place [2][3]. To test the tensile strength of the cam, we developed a simulated crack machined from aluminum bar stock to secure the cam while we applied a tensile force. It is important to note that we wanted to conduct a non-destructive testing regime, meaning that we did not approach the rated strength (14kN) of the cam. We tested the cam at various crack angles (*b)*, to observe the effect of angle on the holding capacity of the cam.

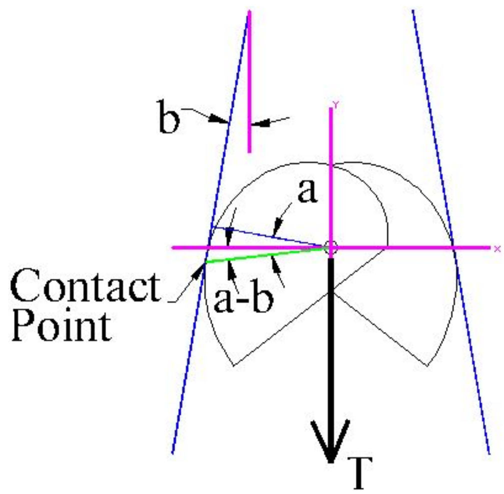


Figure 2: Diagram of Camming Device Operation

NOTE: Our data typically refers to ϴ, which is the net angle between the two angled surfaces, i.e. ϴ = 2b.

2.1 Procedure

1. Machine a large slot into a block of aluminum as described by Figure 3 below (for full drawing see Appendix A, Figure A1). The slot should be at least 50mm deep. After completing the machining, measure the angle between the two angled surfaces and record the value (Approx. 20 degrees for the first trial). Note that only the slot size is important here, the overall block size just needs to be large enough to provide sufficient strength to avoid deformation under high loads.

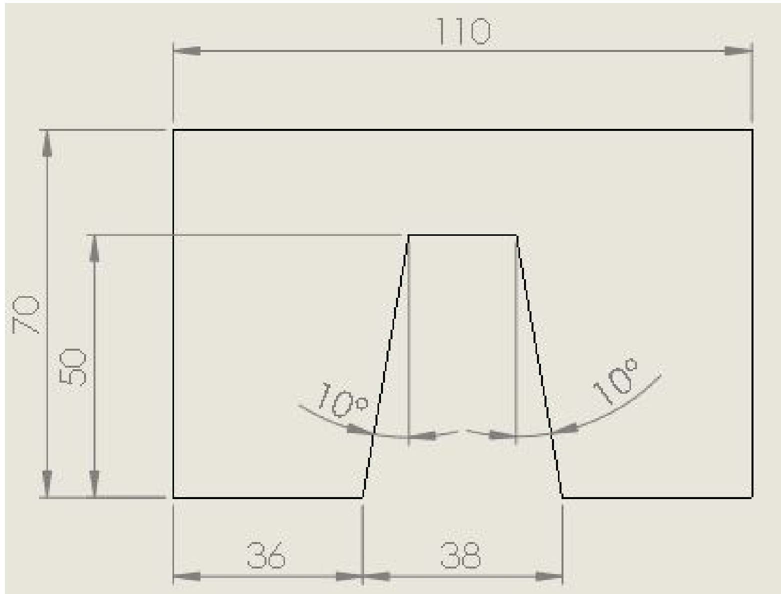


Figure 3: Dimensioned Drawing of Slot

2. Cut a rectangular piece (5cm x 18cm) of P1500 grit sandpaper, and fold it so the rough surface faces inward and outward, and place it inside the metal slot; this simulates a rough surface similar to a rock face that the cam would typically be placed against. Place the cam near the top of the slot, and place the aluminum block and cam on the top shelf of the tensile testing machine. Ensure that the 4 lobes of the cam rest against the same positions on the aluminum block for each of the trials. Secure the loose end of the cam to the bottom shelf of the tensile testing machine (we accomplished this by looping a sling around a metal tube).

Figure 4: Example of Sandpaper and Cam Placement

3. Zero the load reading and max load reading before each trial. Operate the machine at a slow speed of 0.2in/min (force increasing at about 2-5N per second). Increase the load until the cam is pulled out of the slot, or until the load reaches 11kN. Record and export the load force versus deflection data. Repeat this test for at least 5 trials at this angle, using a fresh piece of sandpaper for each trial.
4. Using a milling machine, remove approximately 1 degree from each side of the slot (i.e. reduce the 10 degree measurements in Figure 3 to 9 degrees), so the net angle change is negative 2 degrees. Repeat steps 2-3. Do this for at least 5 different angle measurements.

3.0 MAXIMUM EFFECTIVE LOAD

3.1 Results

For our experiment, we conducted 30 total trials at 6 different crack angles. We observed that the cam became significantly stronger as the crack angle, ϴ, was reduced from ~20 degrees. We started our measurements at an angle of 20 degrees, because initial experimentation showed that the cam's springs would cause it to eject at larger angles. After gathering the raw data from each of the trials, we eliminated the data points created before and after the trials and extracted the maximum tensile load before failure; sample plots of the individual results can be found in Appendix B. We grouped the data by trial number at each of the angles to ensure that the crack surface conditions would be similar for each of the compared sets (i.e. Trial 1 for each angle is on freshly milled aluminum, whereas in the later trials the aluminum has been worn down by repeated tests). The maximum tensile force data is represented for each trial in Figure 5.

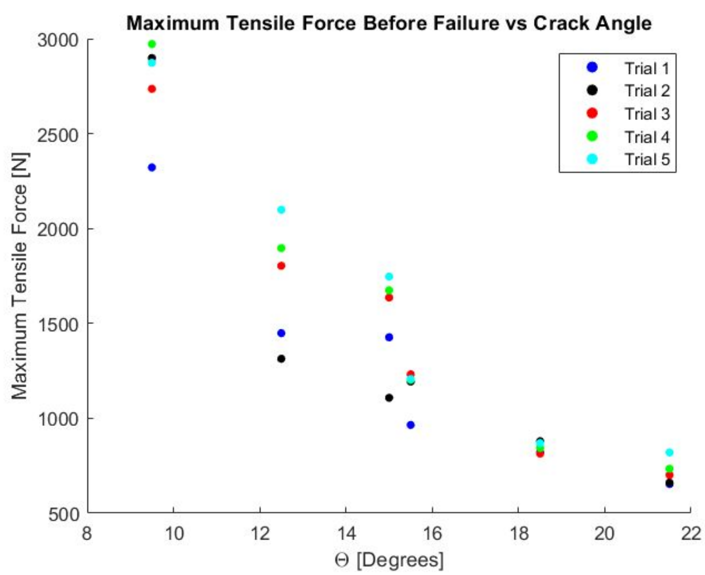


Figure 5: Maximum Tensile Forces by Trial Number

With the observed data, we can predict the maximum tensile force that the cam can be subjected to before failure in future tests. The maximum tensile strength from subsequent trials at the same angle, ϴ, seemed to vary while the general shape of the data was consistent between angles. Our original hypothesis that the cam would be strongest when the angle was 0 is supported by our gathered data. The cam experienced slipping, as discussed in section 4.0, during the trials that could explain the spread in the data.

3.2 Analysis

We created linear, quadratic, and cubic fits for the data sets depicted in Figure 5. The best predictions that we produced were the results of the quadratic regressions that had R-squared values ranging from 92% to 97%. The data trend suggests a non-linear growth equation, which eliminates the linear regression; the cubic regression over-fits the data and produces conflicting equations within the trials; and this leaves the quadratic fit pictured in Figure 10.

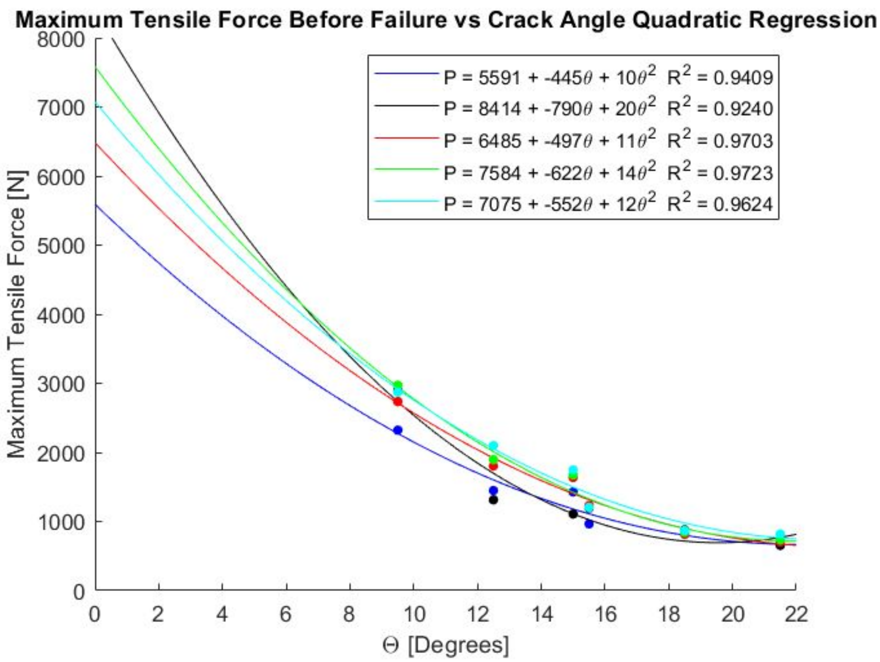


Figure 10: Quadratic Regression of Maximum Tensile Forces

Both the linear and cubic fits can be found in Appendix C for comparison. Because the quadratic fit seems to follow a similar pattern with each data set, we averaged the data and produced a final mathematical description of the relation between the crack angle and the maximum tensile force:

$$P = 7030 - 581\theta + 13\theta^2$$

The averaged relationship is pictured in Figure 11 with single standard deviation error bars to demonstrate the accuracy of the fit.

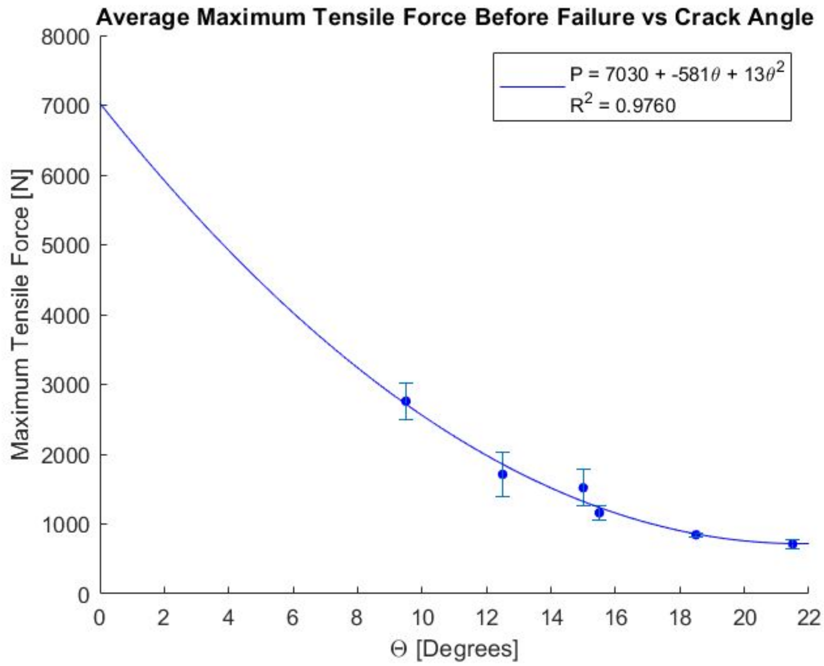


Figure 11: Average Maximum Tensile Strength Relationship with Crack Angle

This particular fit would hold for angles from 0 up to 22 degrees as the function that we produced will begin producing greater maximum tensile forces for larger angles following that point. To produce a more accurate model, we would have to take more measurements and eventually find the position that the cam could no longer carry a load. Our model is accurate for the angles that we observed and can predict the maximum holding capacity of the cam for angles less than our tests, which would occur more often in climbing applications.

3.3 Discussion

We believe that the general trend of increased tensile strength for subsequent trials is a result of the simulated aluminum crack becoming deformed and providing better surface friction. Ideally, we would gather more data in the angle ranges both below and above the data that we've gathered to improve our model; however, we believe that the relationship that we have produced is acceptable.

We attempted to calculate a mathematical relationship between the tensile force, P, and the angle of the crack opening, Θ, but we arrived at the conclusion that the cam is designed to amplify the applied tensile force as a normal force that creates friction on the crack walls. The dependence of the friction force on the applied tensile force theoretically causes a no-slip condition for the cam that means that the cam will not eject from the crack without experiencing material deformation. The proportional relationship of the normal force, and therefore the friction force, to the applied tensile force is amplified as the crack angle increases, which is what causes the reduction in max tensile force as the angle is increased. In our trials, we believe that the simulated crack material was deformed once the applied force became large enough and that was the cause of both the initial slipping that we observed and the final ejection.

The material that the cam is inserted into will ultimately decide the maximum tensile strength of the cam; however, the general relationship that we observed will hold between materials. This means that the relationship that we obtained would be shifted by a constant that could be determined from the material being tested. A more robust testing regime would be necessary to fully characterize the relationship between the crack angle and maximum tensile strength; various sizes of cams would need to be tested in various materials with angles from 0 degrees to the point of failure of the device to completely describe the relationship. In this testing scenario, the point of failure of the device would be when the cam could no longer hold a load in the crack.

4.0 SLIPPING

4.1 Results

One of the unexpected results of our experiment involves how, under a given load, the cam can slide down the crack surface slightly and then re-engage and continue to hold an increased load. Figure 6 provides a visual example of this phenomenon. While we were not explicitly testing for this, the conclusions drawn could provide some valuable insight on cam behaviour for climbers. We observed that the first major slip would occur once the load became greater than ~80% of the maximum load, but prior to the first major slip, there would often be some minor slipping as the load was increasing; this is demonstrated in Figure 7.

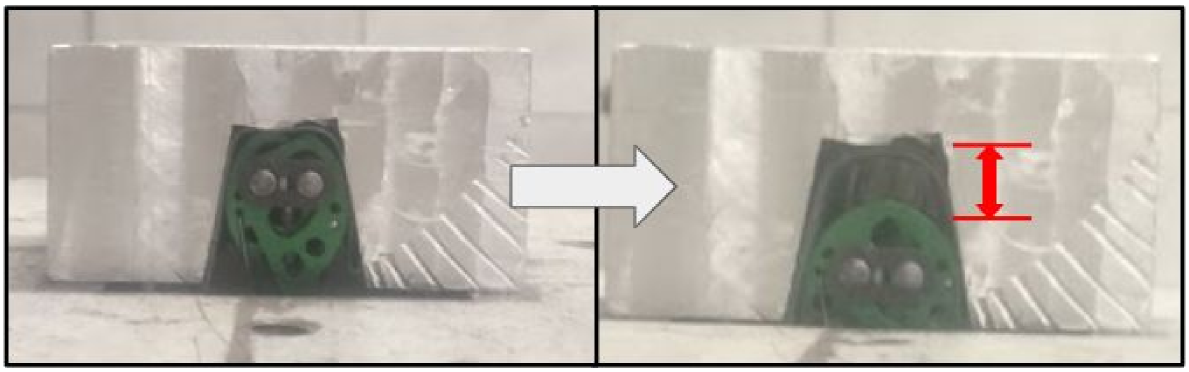


Figure 6: Cam Slipping from Seated Position

The trial observed in Figure 6 continued following the slip denoted by the red measurement. An interesting note is that the sandpaper typically stayed in place, indicating that the friction between the sandpaper and the aluminum block was greater than the friction between the cam and the sandpaper.

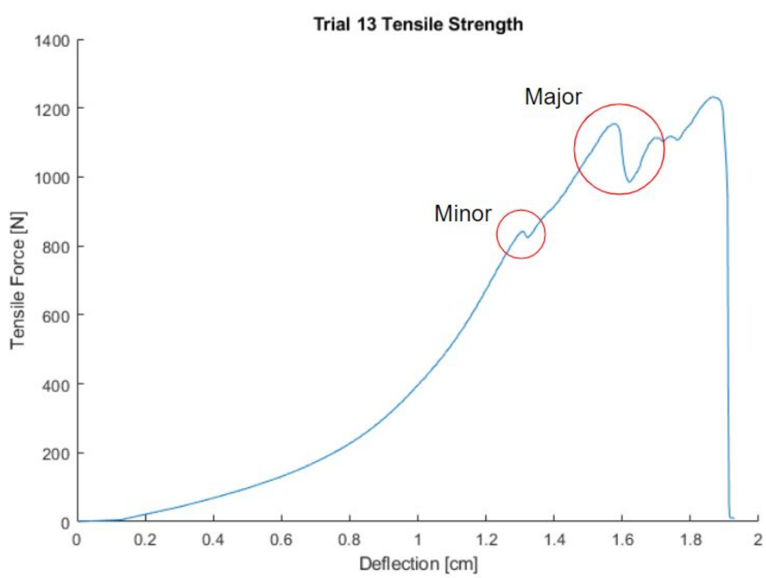


Figure 7: Minor and Major Slips During Tensile Testing

NOTE: Trial 13 here is equivalent to Trial 3 for the third angle tested. Trials 1-5 were for the first angle, Trials 6-10 for the second angle, etc.

We found that as the angle increases, the first major slip load became significantly smaller relative to the max load, which can be observed in Figure 8.

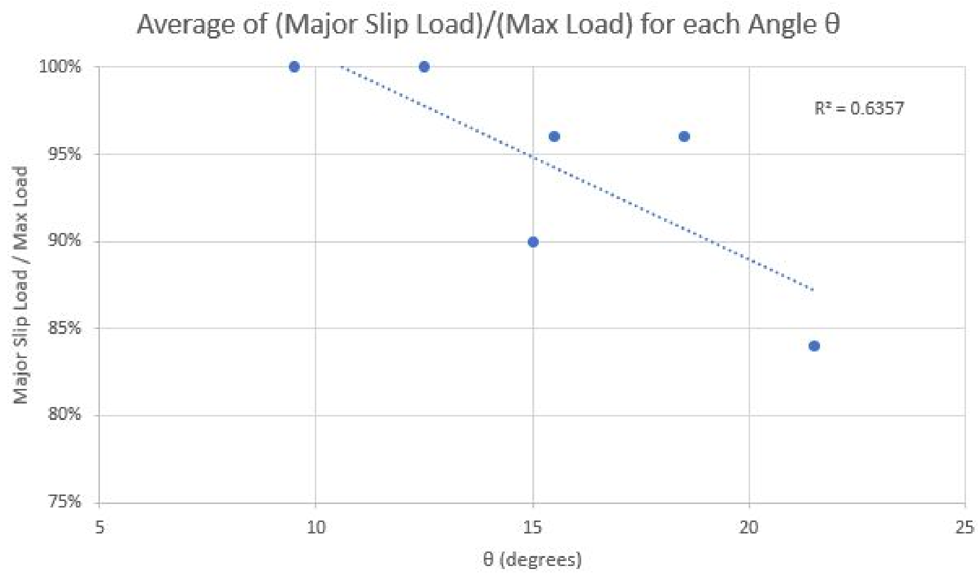


Figure 8: Major Slip Load Patterns Averaged for Each Angle

This suggests that when the cam is in a small angle placement, the cam will not slip until it completely fails. We also found that cams in large angle placements are more likely to experience minor slipping before major slipping as demonstrated in Figure 9. Note that there were five trials for each angle.

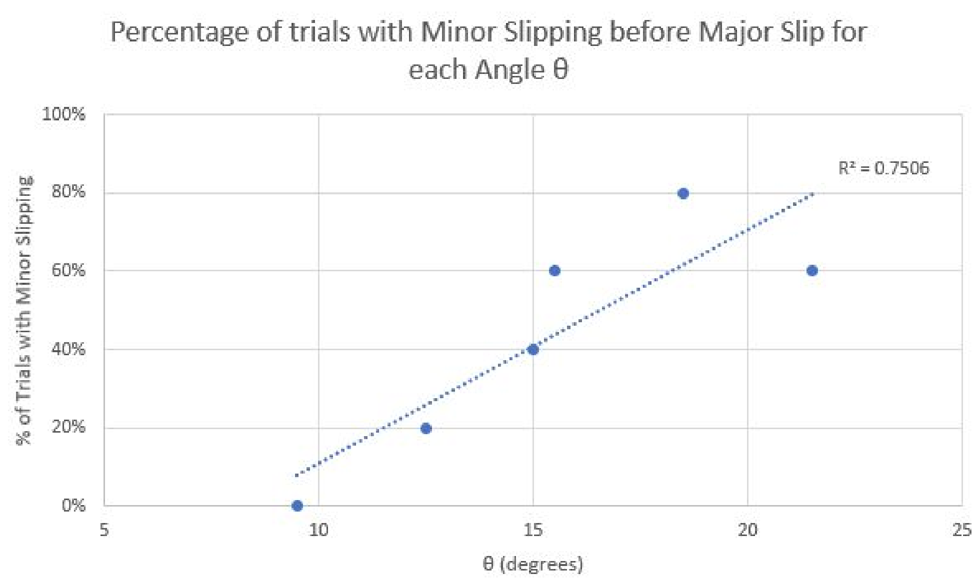


Figure 9: Minor Slip Likelihood for Each Angle

4.1 Analysis

For the slipping analysis described in Figure 8 and Figure 9, we went through each trial individually and recorded the load force at the first major slip point. It was also noted whether there was significant minor slipping before the first major slip. This was largely a subjective process, but for the majority of the trials it was very clear what type of slip was occurring in each case. If it were a very large dataset, a systematic approach (i.e. a 10% decrease in total load force = major slip) would be a more efficient way to characterize the data.

4.2 Discussion

Climbers like to load-test their gear as they place it, either by pulling on it or by putting their weight on it. If the cam slips slightly but still manages to support their weight, a climber may think that the placement is okay, but our results demonstrate that the slipping means the cam is near its max load and may be unable to arrest a fall.

We also discovered that for large angles, minor slipping is a likely occurrence. This is significant for climbers because if a cam is placed is a very shallow slot, sufficient slipping may cause the cam to eject from the slot before reaching its max load.

Since we were not intentionally testing for this, our trial numbers for each case are too small to conduct a proper analysis and draw accurate conclusions. However, our data points towards some interesting trends, indicating that this is a possible avenue for further research.

5.0 SOURCES OF ERROR AND AVENUES FOR FURTHER RESEARCH

One of the most important factors in effective cam strength is the friction between the cam and the crack surface. Our experiment used sandpaper wedged between the cam and an aluminum, which is a highly unrealistic scenario for actual climbing environments. This experiment could be greatly improved by building a jig that uses granite, limestone, sandstone, or other surfaces that are more common in climbing. This was our intention when beginning the experiment, but it was too complex for us to achieve given our timeframe and budget.

Another important factor that was neglected in our experiment is that the stress on the cam is typically dynamic, such as when the climber is falling. Our experiments used a slowly increasing static load, but it would be more realistic to shock load the protection equipment. However, not all loads in climbing are dynamic, as climbers often use static anchors for various purposes, such as aid climbing and using portaledges.

This experiment could also be extended by examining the cam throughout its entire camming range, or by testing different sizes and brands of cams. There is lots of variety in cam shapes and sizes, and their performance may differ significantly.

Another path of interest is measuring the effect of wear due to repeated placements in the same position. In rock climbing, it is very common for people to place their gear in exactly the same spots so this would provide valuable information for climbers. In our experiment, we found that generally the more worn the aluminum jig was, the higher the maximum load was. However, we started from a smooth aluminum surface, so this may not be true in a real rock environment. For example, granite is already quite rough, so repeat placements may actually smooth out the granite surface and reduce the maximum load of the cam.

There were also some less significant sources of error. The tension testing machine we used for this experiment was not calibrated by us, so the true accuracy of the machine was unknown to us. It is also unlikely that the angle on one side of our jig was exactly equal to the other side, therefore the cam was slightly offset in the jig which may have had an impact on its performance. Higher precision milling and angle measurements would offer some small improvements in this area.

6.0 CONCLUSION

The goal of this experiment was to provide climbers with some useful knowledge of effective cam placements. The conditions of our experiment were not specific enough to provide direct, numerical information to climbers, but our analysis revealed some interesting patterns and relationships that would still be useful to the climbing community. We found that effective cam strength increases quadratically as a function of crack angle. We also found that cams are more likely to slip slightly in large angle crack formations, therefore cam placements in shallow, large angle cracks have a chance to eject before reaching critical strength. Also, a slipping cam indicates the applied load is nearing the maximum load (within 20%). Repeat placements in the same location may also cause significant wear on the surface of the crack. This affects the effective cam strength in that position, but it may depend on the initial state of the crack surface.

7.0 PERSONAL REFLECTIONS

The initial scope of experiment greatly exceeded what we were actually able to execute. We ran into lots of hurdles, causing us to narrow down the scope of our experiment. A small budget limited us to only testing one type of cam, as well as a limited number of trials because the material for building a strong enough jig was expensive. We also didn't run as many trials as we were hoping to due to difficulty in gaining access to the stress lab. We intended to have about 20 angle measurements from 0 to 20 degrees, but in the end we only managed 6 unique angles. An important lesson we learned in this experiment is to choose projects that are more simple and focused so that the results can be more accurate. Given more time and a larger budget, the tests that we performed could be more robust and provide a much more useful result.

8.0 ACKNOWLEDGEMENTS

Thanks to:

- Dr. Schajer for providing guidance and helping us with materials and equipment.
- Ian Van der Wee for lending his climbing equipment for initial experimentation.
- The experts in the machine shop for helping us refine our jig design, and for providing assistance with the milling.

9.0 REFERENCES

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9.1 Images

http://www.vainokodas.com/climbing/spir1.gif. (2019). [image].

http://www.vainokodas.com/climbing/spir2.gif. (2019). [image].

https://www.climbing.com/.image/c_limit%2Ccs_srgb%2Cq_auto:good%2Cw_275/MTM1MjQ2NzY0NTgzMjA4OTcw/tech-tip--trad----making-the-call.webp. (2019). [image].

http://thetravelingnaturalist.com/resources/cam%20placement.jpg. (2019). [image]

10.0 APPENDICES

10.1 Appendix A

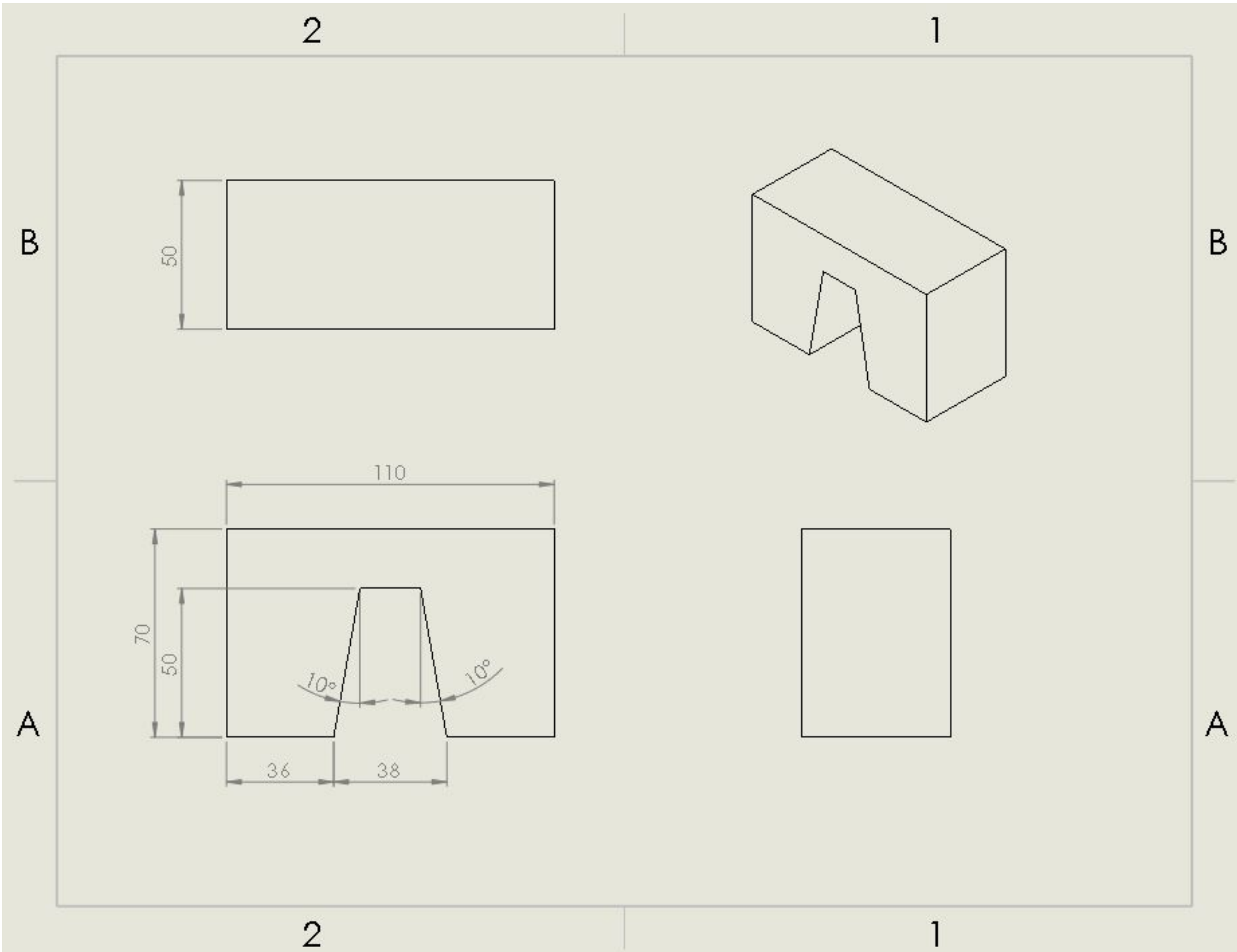

Figure A1: Technical Drawing of Aluminum Block and Slot

10.2 Appendix B

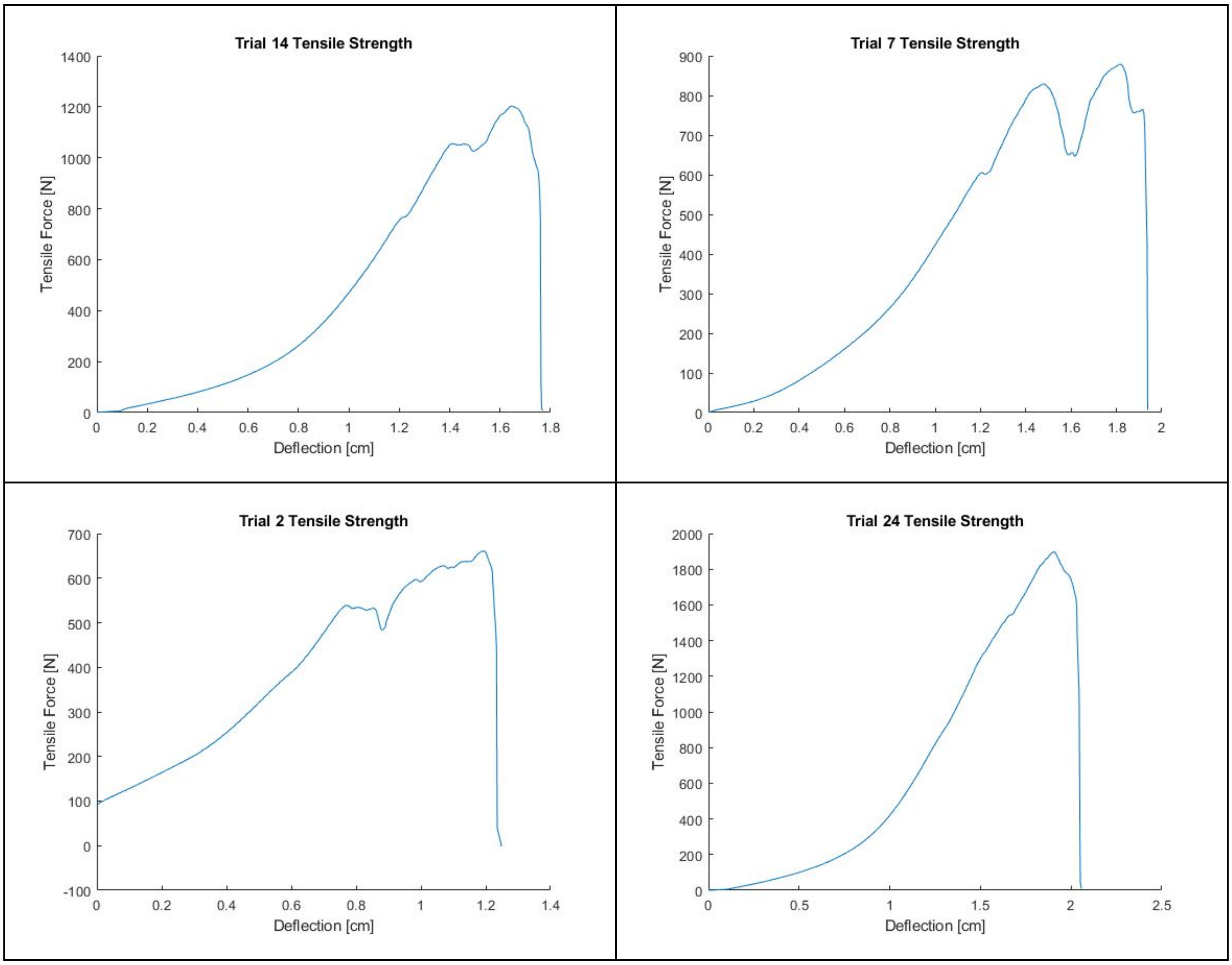

Figure B1: Examples of Tensile Strength Test Results

NOTE: Trial 14 here is equivalent to Trial 4 for the third angle tested. Trials 1-5 were for the first angle, trials 6-10 for the second angle, etc.

10.3 Appendix C

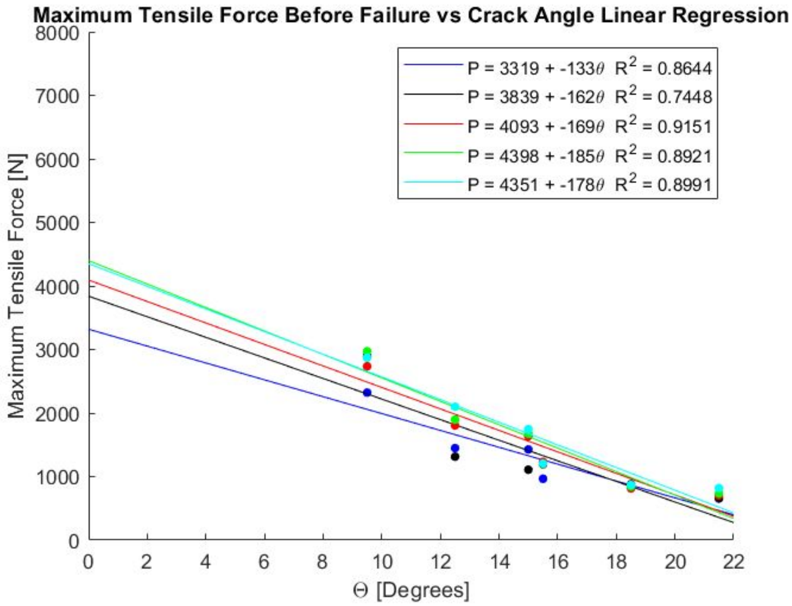

Figure C1: Linear Fit of Maximum Tensile Force

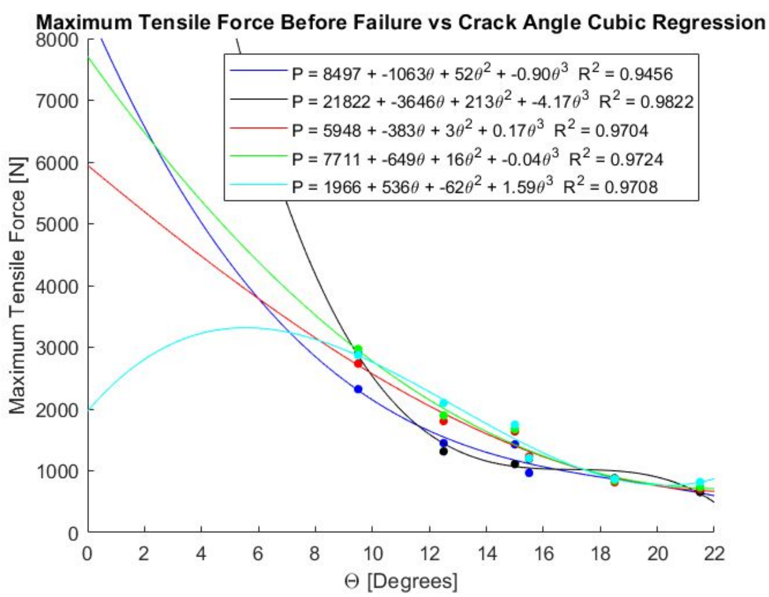

Figure C2: Cubic Fit of Maximum Tensile Force