CARABINER TESTING

Final Report

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1 Abstract

Carabiners are safety devices used to connect ropes to a climber's harness or to a rock face. They are metal links most commonly made of aluminum. The standard industry practice for testing and rating the strength of carabiners is by single pull to failure tests. These tests yield the maximum tensile strength of the carabiner. However, in the field, carabiners do not break in a single pull. They have only been known to break after multiple loads, suggesting a fatigue failure. In order to provide the climber with more relevant information about the lifetime of carabiners, this project has seen the completion of the first comprehensive cyclic testing performed on these devices. All tests were performed on Black Diamond Light D aluminum carabiners rated at 24kN. This type of carabiner was chosen because it is the most common type used by climbers today. A load cell was used to apply cyclic loads to the carabiners at load magnitudes reflecting actual in-field use. The major result of the project was the generation of a load vs number of cycles to failure curve for the carabiner. From this data, a new method for testing carabiners was proposed based on the number of cycles to failure rather than the maximum tensile strength.

2 Background

Climbers rely on an intricate series of inter-connected static and dynamic ropes, webbing, and safety harnesses to secure themselves to the surfaces that they are scaling.[1] When climbers lose their grip, this equipment serves as a safety mechanism, preventing falls that would otherwise result in serious injuries and sometimes death.

Climbers use carabiners to connect and secure ropes, webbing, and harnesses. Most commonly during field use, a carabiner serves as a link between a rope and a piece of webbing. A carabiner is a loop-shaped mechanism equipped with a spring-loaded opening latch or gate that is vital to climbers for connecting climbing ropes to harnesses and other safety gear. Carabiners are made of a number of different metals and in various shapes. Most carabiners are composed of aluminum; specifically, they are commonly made of 7075 heat forged aluminum. The most common shape for a carabiner design is a "D" shape (Figure 1). The locking mechanism for the opening gate of the carabiner also varies widely among carabiner designs. The design requirements of a carabiner are (1) that it must hold static loads of climbers and equipment and (2) that it must withstand large dynamic loads that it may be subjected to during climbing falls. All carabiner designs must be able to withstand a 20kN load or greater. Optimum carabiner designs maximize strength while minimizing the weight of the carabiner.

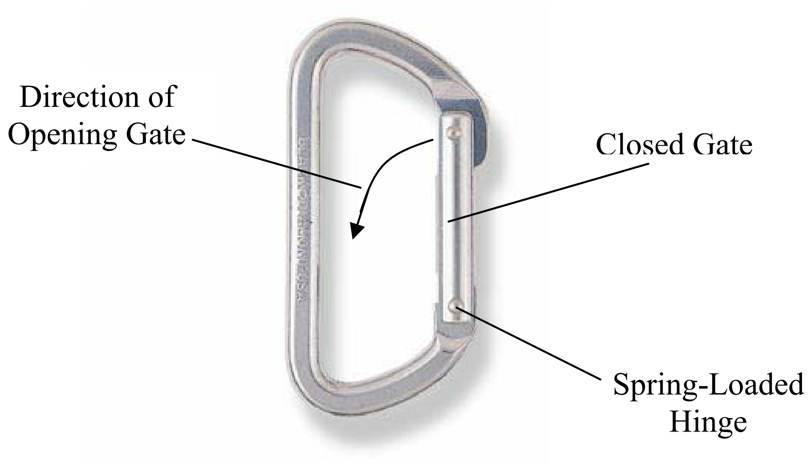

Figure 1: A standard "D" shaped carabiner with spring –loaded gate on right. (http://www.blackdiamondequipment.com/rockclimbing/biners_light_d.html)

3 Motivation

Under normal climbing usage, a carabiner rarely breaks; however, such failures do occur and can be fatal. The current standard method for strength rating carabiners is a single tensile pull to failure. The carabiner is placed in a load cell and the load on the carabiner is increased linearly from zero until it breaks into two or more pieces. The load at which the carabiner broke is recorded as the maximum strength for that particular carabiner design. The average carabiner is rated at a maximum strength of about 20 to 30kN.[2] These current carabiner testing and strength rating methods do not accurately simulate actual loading conditions that climbers subject carabiners to. The rating system does not provide enough information to the climber because carabiner use entails repeated tensile loading of less than 10kN on average.[3] The climber is not as interested in maximum load as he/she is in carabiner lifetime under normal repeated use.

Climbers would most likely also be interested in the fatigue failure characteristics of carabiners in the open gate condition. The carabiner in figure 1 is in the closed gate position. Open gate carabiners have been known to fail in the field. The carabiner gate can become stuck in the open position due to ice or wear. Also, since the gate is mounted on a spring-loaded hinge, the gate can temporarily swing open while the carabiner is being loaded if it is knocked against a rock. An open gate carabiner is much weaker as the load is only distributed along the spine. When the gate closes and completes the loop allowing the force to be distributed along both the spine and the gate, the maximum tensile strength of the carabiner roughly triples. This project investigates both the open and closed gate conditions of the carabiner in order to completely and accurately model potential field use of carabiners.

The knowledge gained in this project will result in a more informative strength or lifetime rating for carabiners. Such improvements will result in a more reliable product that produces greater profits for climbing gear manufacturers. More importantly, climbers will be safer. Carabiner modifications resulting from this project are intended to reduce the number of accidents that result from the failure of old or overused carabiners.

4 Objective

The primary goal of this project was to enhance the testing and rating standards of carabiners by determining deformation and failure characteristics that reflect the use of carabiners in the field. The experimental design developed a methodology for testing current carabiners that replicated the static and dynamic forces that climbers exert on carabiners. These new methods were intended to investigate elastic and plastic deformation qualities, including fatigue curves, and to define a carabiner's safe lifetime in units of number-of-uses, or more specifically, number-of-falls.

5 Previous Work

In 1992, the American Society for Testing and Materials (ASTM) developed the procedural standard for testing and strength rating of carabiners.[4] The experimental methods ASTM prescribed are still used today and serve as a basis of comparison among carabiner designs. These methods are applied in a variety of standardized tests that ensure carabiners and carabiner manufacturers meet minimum safety requirements. ASTM tests carabiners with a single tensile pull-to-failure method in the closed gate, axial loading condition. The carabiner is placed in a tensile loading machine by hooking it between two 13mm diameter steel dowels. The carabiner is initially under zero load. The load on the carabiner is then increased linearly as the tensile loading machine slowly pulls the two steel dowels apart. The value of the load at failure becomes the strength rating for that particular carabiner design. Failure is defined by the carabiner breaking into two or more pieces. These are the standard strength rating procedures that will be built on and improved in this project

Dave Custer and Dave King of MIT performed tests designed to collect data on climbing equipment in 1995.[5] Their experimentation was not focused on carabiners; however, carabiners were used in order to attach ropes and other equipment during testing. Many of these carabiners were observed to fail, or break, under repeated loading in closed gate conditions. On average, the carabiners were observed to fail after six loads of 12kN.[6] Their findings indicate that carabiners do indeed fail under repeated loading at loads less than the ASTM specified maximum load. These failures occurred even in the absence of open gates or unusual loading conditions. Therefore, carabiners do indeed break when subjected to repeated loads less than that of the maximum tensile strength of the carabiner, and not only at single loads greater than the maximum strength.

Most recently, Michael Walk performed the first cyclic loading tests of carabiners. During this experimentation, it was determined that after half a million cycles between 0 and 2kN, the gate of the carabiner displaced, or opened, one micrometer.[7] This displacement was measured while the carabiner was in an unloaded condition, proving that carabiners plastically deform under low magnitude cyclic loads. Therefore, comprehensive plastic deformation data on carabiners can be used to predict when a carabiner is near failure.

6 Technical Approach

6.1 Overview

During the experimentation in this project, carabiners were tested under two different loading conditions, the closed gate condition and the open gate condition. These tests were designed to replicate the ASTM methods of rating carabiners by clipping them directly to steel dowels while load is applied.

The carabiners were tested at a variety of different load values designed to replicate field use. Each carabiner will be cycled between zero load and a specified maximum load. The maximum loads that were tested for the closed gate condition range from 8 to 20 kN. Specifically, cyclic tests were performed at every 2kN interval within this range. This is the high end of the load range that carabiners experience in the field. Cyclic testing of carabiners at these higher maximum loads ensures that the carabiners will eventually break and limits the time required for each test. In the field, carabiners can be loaded anywhere between 0 and 20kN. The maximum loads tested in the open gate position were 4, 5, and 6kN. The ASTM rated maximum tensile strength for the carabiner used in this project in an open gate position is 7kN. Tests were not performed below 4kN as such tests could not be completed within a reasonable amount of time.

A variety measurements and observations were taken during the experimentation associated with this project. Quantitative measurements include the number of cycles to failure. This measurement will be taken at both loading conditions and at all load values to generate two S-N curves, or curves plotting maximum stress versus number of cycles to failure. Displacement and plastic deformation measurements were taken as the shape of the carabiner changes from applied loads. Finally, qualitative observations of crack formation and propagation were performed. Further qualitative observations of the general deformation characteristics of the carabiner were also performed.

Two steel grips (Figure 2) were machined according to the specifications of the ASTM test apparatus for single pull to failure testing on carabiners. The grips hold the carabiner in place while it is loaded and allow the carabiner to assume a "natural" position, or a position such that the steel dowel applies load to the carabiner in the location where the rope would naturally fall into place when a carabiner is used in the field. The carabiner is clipped around the lower pin of each grip.[9] The upper pins attach the grips to a connecting piece (Figure 3).

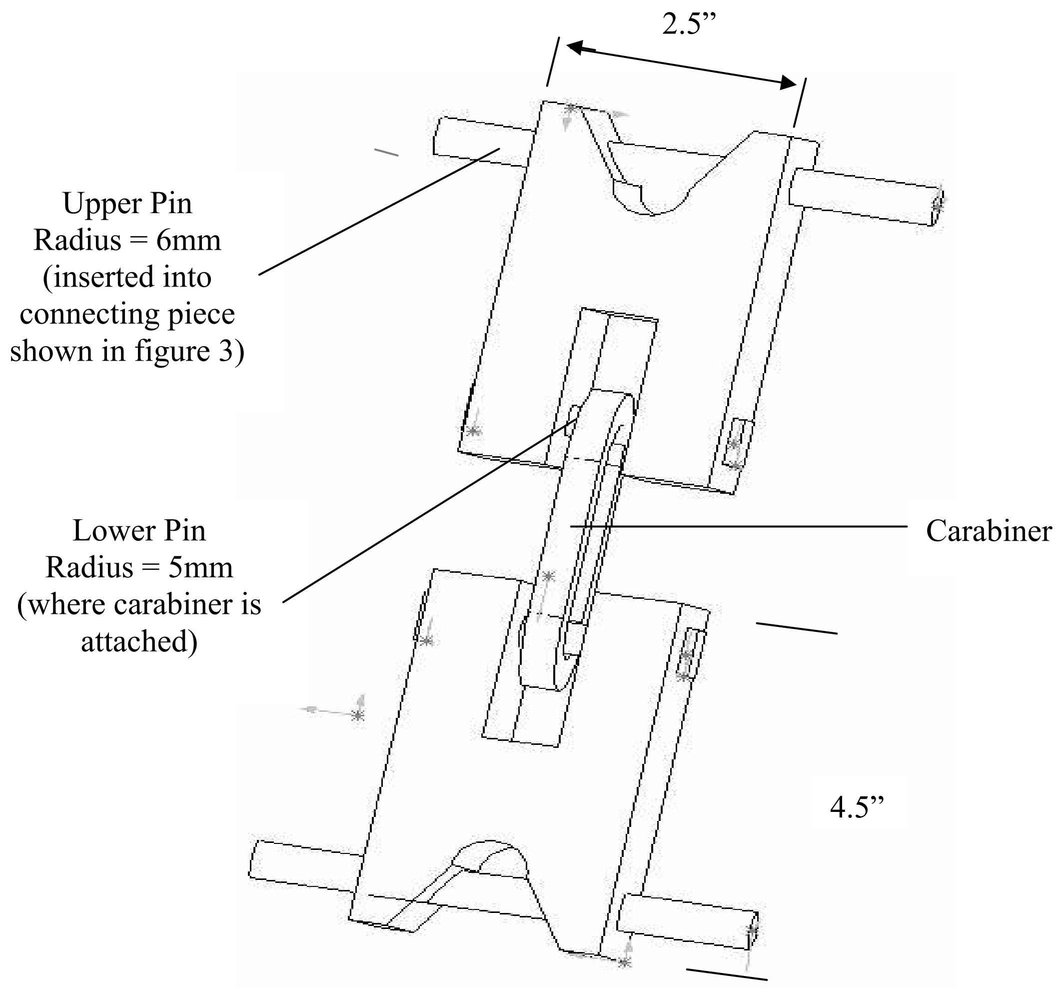

Figure 2: The two steel grips designed according to standard ASTM apparatus. Rotating pin is inserted into MTS tensile loading machine. Carabiners or spectra webbing are looped around non-rotating pin.

In order for the grips to be compatible with the MTS tensile loading machine, an extra steel connecting piece (Figure 3) was machined to attach to the upper pins of the grips shown in Figure 2. The piece is designed to rap around the rotating pin of the grip to allow the grip to move freely and position itself with respect to the loaded carabiner. The opposite end of the connecting piece is a 3” by 1” rectangle that fits inside the vice clamp of the MTS machine. This holds the connecting pieces in place while the rest of the apparatus is free to rotate about the four steel pins.

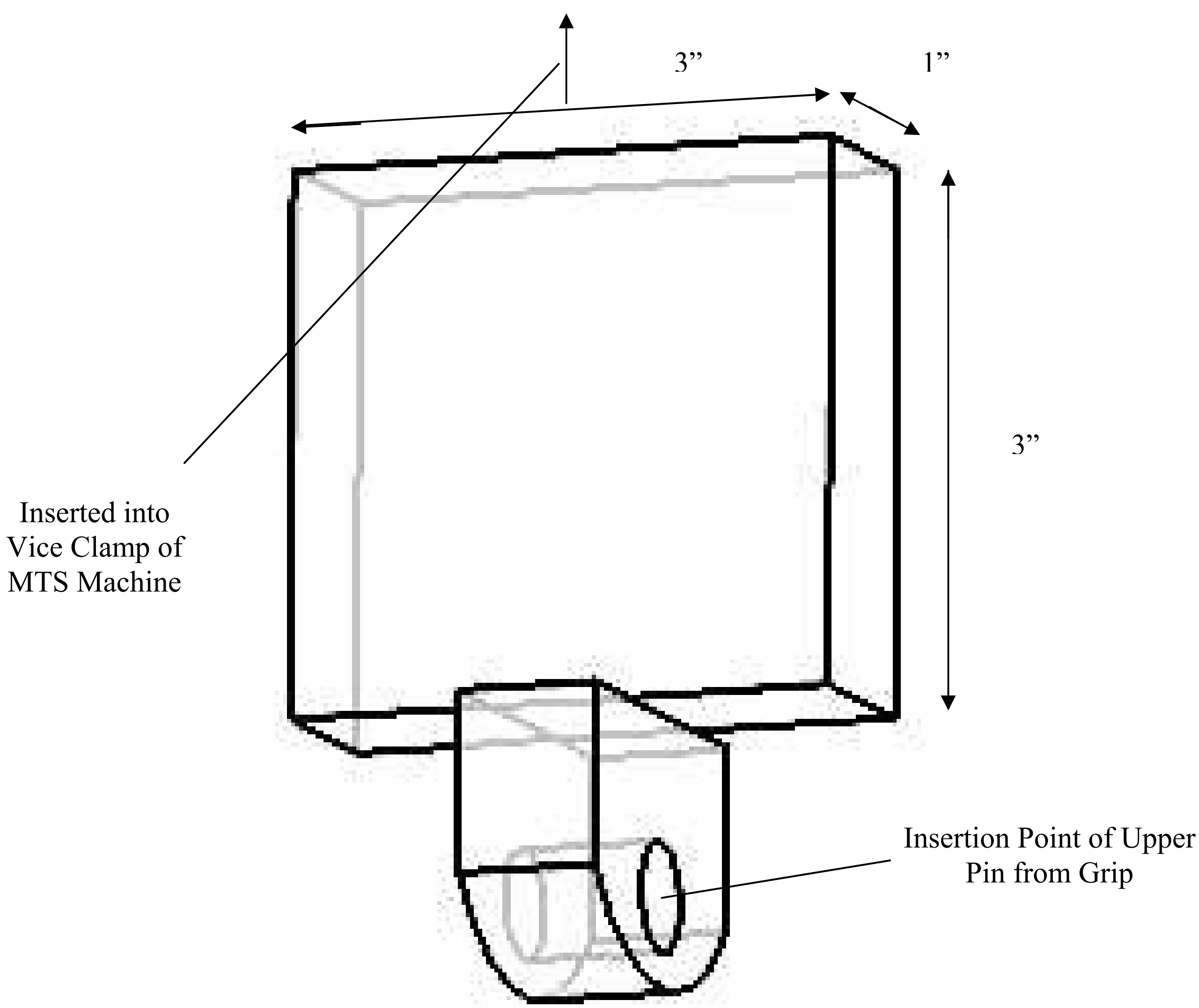

Figure 3: Steel connecting piece between ASTM standard grips and vice clamp of MTS loading machine.

6.2 Load Conditions

The two steel grips (Figure 2) were machined to ensure the compatibility of the carabiners to an MTS tensile loading machine (Figure 4). This machine applies the load to the carabiners.[8] The grips were machined to emulate the standard test apparatus developed by the ASTM to produce results for which current strength rating standards may be used as a reference point.

Therefore, the test apparatus is virtually identical to that of the ASTM. However, the method differs greatly as this project loaded carabiners cyclically to emulate in field use rather than loading in a single pull to failure as the ASTM does.

Furthermore, tests were performed at two separate load conditions, the open gate condition and the closed gate condition. The gates of the carabiners intended for open gate testing were sawed off in the Aero/Astro machine shop.

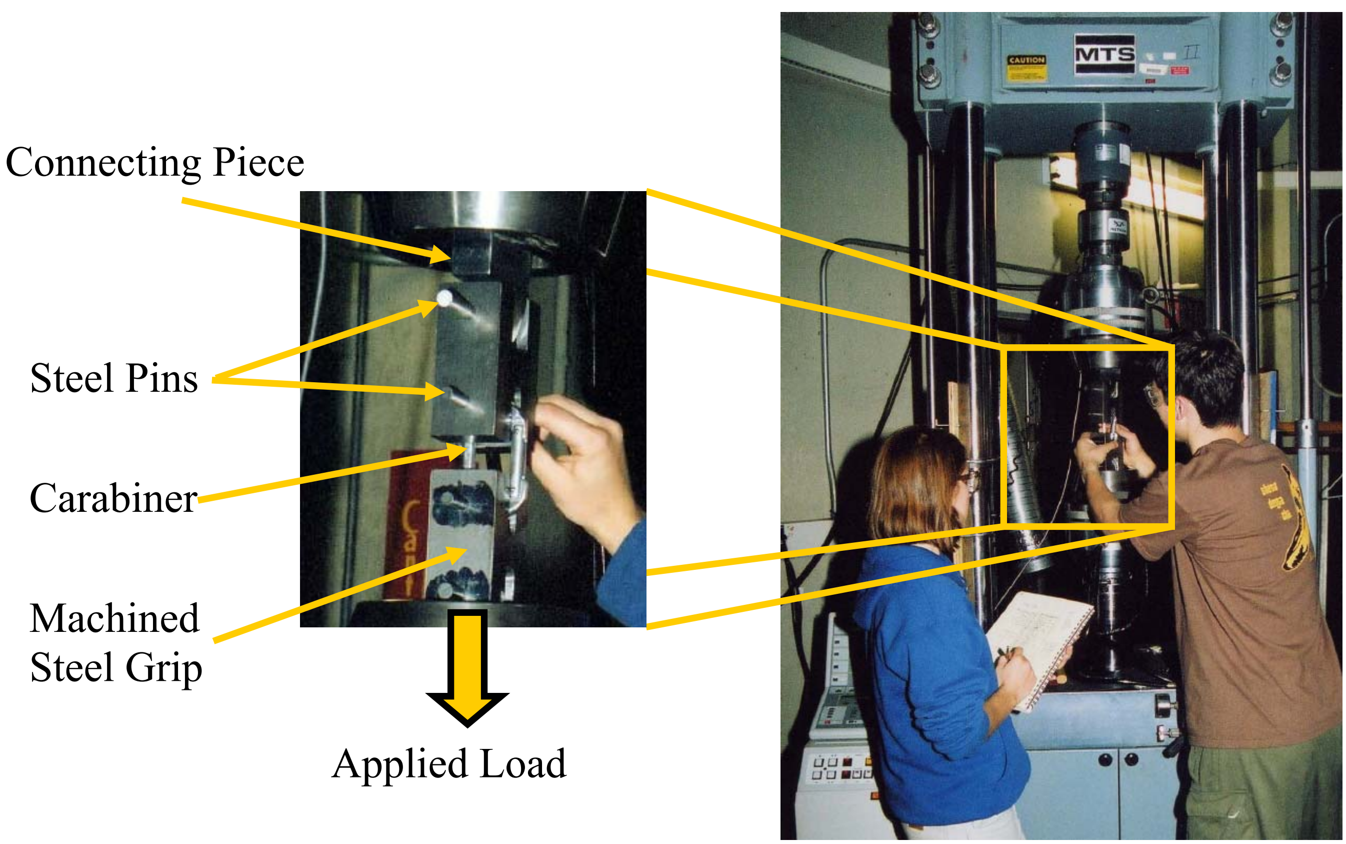

Figure 4: Photo of MTS tensile loading machine and blowup of machined test apparatus

6.3 Load Values

Within each loading condition, the carabiners were tested at a variety of different load values. During each test, a carabiner was cycled between 0.5kN and a maximum load. The maximum load value varied among tests. The majority of testing employed the closed gate loading condition. At this condition, carabiners were cycled to maximum loads from 8 to 20kN at 2kN increments. The load range chosen for the tests only goes as high as 20kN as this amount was calculated to be the worst-case scenario for a fall taken on a carabiner in the field. Climbers normally attach a carabiner to the rock face every 1.5 meters during their ascent. This means that the furthest distance the climber will ever fall is 3 meters. If the climber was 90kg (200lbs), the force on his/her body due to the fall is 12kN. Due to the stretching of the rope and friction, the climber holding the other end of the rope only feels 8kN of pull. Therefore, the carabiner is loaded to a total of 20kN (Figure 5).

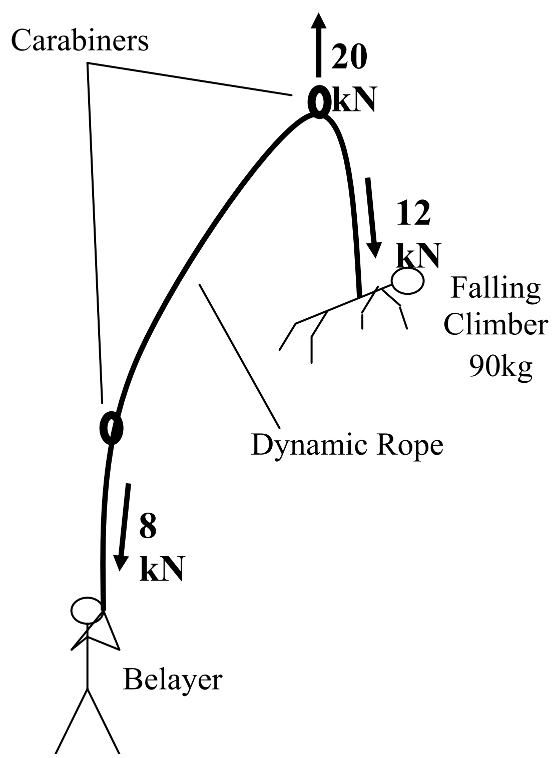

Figure 5: Schematic of "worst-case" scenario climbing fall. Illustrates the conditions of the largest potential in-field load on a carabiner.

Testing in the open gate position was more limited, cycling carabiners to maximum loads from 4 to 6kN. Each cycle of load for every test in both conditions was applied to the carabiner sinusoidally with a period of 0.5 seconds. This is the average amount of time a carabiner is loaded during a climber's fall.[2] A sinusoidal load also portrays how load on a carabiner during a climber's fall increases over time due to the stretching of the rope. In field use, a carabiner is not loaded linearly or by impulse.

The length of time required to complete a cyclic loading test on a single carabiner was expected to be greatest at the lowest load values. This is also the condition at which the number of cycles to failure was expected to be greatest. Again, failure was defined by the carabiner breaking into two or more pieces. The number of cycles to failure was expected to be greatest during the 0.5 to 8kN cyclic tests. Data provided by the MIL-HDBK-5G and information obtained through loading a Solid Works model of a carabiner using NASTRAN finite element analysis indicated that a carabiner made of 7075 Aluminum cyclically loaded between 0 and 8kN will fail at fewer than 10,000 cycles. Therefore, because one cycle is completed every 0.5 seconds, the greatest possible length of time necessary to complete was expected to be less than 1.5 hours.

6.4 Quantitative Measurements

The MTS tensile loading machine outputs measurements of load and displacement that was written to a computer for post-processing. The MTS machine will also counts the number of cycles during each test. Strain gauges were attached to the spines of some the carabiners that were tested (Figure 6) to measure very small values of displacement on the surface of the spine.

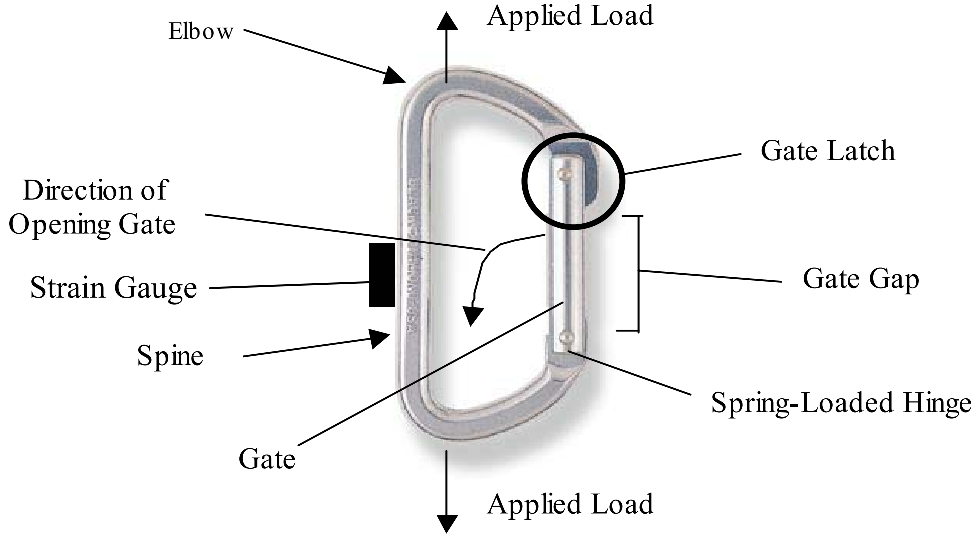

Figure 6: A standard "D" shaped carabiner displaying strain gauge and load placement. Gate opens down and left from gate latch and pivots on spring-loaded hinge. (http://www.blackdiamondequipment.com/rockclimbing/biners_light_d.html)

A micrometer was used to measure larger values of displacement in the gate gap (Figure 6) of the carabiner as the carabiner plastically deforms. In order to take these measurements, the carabiner was removed from the MTS machine periodically during the cycling. Therefore, the micrometer measurements were taken while the carabiner was in an unloaded condition. At zero load, any measured displacement was the result of plastic deformation. The micrometer was also used to measure the size of the cracks on the fracture surface of the broken carabiners after they had been cycled to failure.

6.5 Qualitative Observations

In addition to the measurements taken during each test, qualitative observations of cracks and deformation were performed. The purpose of these observations was to note the location of stress concentrations and crack formations in the surface of the carabiner and to determine the number of cycles at each load required to produce these cracks. Therefore, they were only performed at the lower cyclic load values. Specifically, the observations were made during all tests at either 8 or 10kN. During these experiments, crack propagation was expected to be the slowest and the number of cycles between crack formation and carabiner failure will be greatest. Therefore, it was more likely that cracks and high stress concentrations would be observed during these tests.

A Torrex 150D x-ray machine was used to take photographs to look for the early formations of cracks that would not be detected by the human eye. During testing, when the carabiner was near failure, it was removed from the MTS tensile loading machine and coated in an iodine penetrant solution. The carabiner was then x-rayed. If any cracks had formed in the carabiner surface, the iodine would have seeped into the crack to become visible in an x-ray photograph of the carabiner.[11] These observations were performed at the low end of the tested load range; specifically, at the 8 and 10kN conditions. This is where the propagation of the cracks was expected to be slowest and easiest to catch between cycles.

7 Test Matrix

Table 1 depicts the test matrix for this project. As mentioned before, the bulk of the testing was performed with the closed gate configuration as this is how carabiners are most commonly used in the field. Only three tests were performed at the 8 and 10kN conditions of the closed gate configuration since these tests required almost twice as much time to perform than the other test in the closed gate configuration. However, the goal was to perform at least three runs for every load condition in order to have accurate data. Additionally, The 12 to 20kN range data will complete the S-N curve for the carabiner design tested. The iodine penetrant x-ray photography was only performed at the 8 and 10kN maximum load conditions because this is where the development of stress concentrations and cracks would occur slowest. Hence, there was the greatest chance of finding these concentrations and cracks in observations performed at such conditions. Strain gauges were placed on spines of three of the carabiners tested. Strain gauge measurements were taken at the low end of the load range at 8 and 10kN where change was expected to occur slowly. Another strain gauge was placed on the spine of one of the carabiners tested at 20kN to record the effects of large magnitude loads on the spine. During each test, the carabiner was periodically removed from the MTS machine to take measurements of the gate gap displacement while the carabiner was under zero load.

Cyclic Load Range (kN)	Number of Carabiners Tested	
	Closed Gate Configuration	Open Gate Configuration
0.5 - 4	-	3
0.5 - 5	-	3
0.5 - 6	-	3
0.5 - 8	3*^	-
0.5 - 10	3*^	-
0.5 - 12	4	-
0.5 - 14	4	-
0.5 - 16	4	-
0.5 - 18	4	-
0.5 - 20	4*	-

"*" denotes 1 carabiner broken with strain gauge measurements taken

"^" denotes at least 1 carabiner with x-ray observations performed

Table 1: Test matrix outlining the number of tests, measurements, and observations that will be performed at each load value and for both the closed and open gate configurations.

8 Results

8.1 Fatigue Testing

The major component of the results for this project was the data recorded on the number of cycles to failure for each of the tests which provided the S-N curves that were sought for both the open and closed gate conditions.

Cyclic Load Range [kN]	Number of Tests Performed	Average Cycles to Failure	Range of Cycles to Failure	Variance [%]
0.5 – 4	3	7849	6901 - 9694	20.36
0.5 – 5	3	3351	2974 - 3740	11.46
0.5 – 6	3	1775	1309 - 2098	23.28
0.5 – 8	3	10939	9554 - 12775	15.15
0.5 – 10	3	5533	4785 - 6226	13.05
0.5 – 12	4	2959	2693 - 3608	20.07
0.5 – 14	4	1556	1340 - 1988	19.08
0.5 – 16	4	1182	989 – 1408	17.68
0.5 – 18	4	751	489 – 950	24.42
0.5 – 20	4	263	194 – 312	19.45

Table 2: Average number of cycles to failure, range and percent variation for each maximum load condition. The first three rows of this table correspond to the open gate tests performed at the lowest load values. The rest of the data corresponds to the closed gate tests.

The percent variation displayed in the far right column was derived by dividing the standard deviation by the mean. This value quantifies the accuracy of the data. A large variance suggests that more tests could be performed at that load value to find a more accurate mean and possibly identify some data points as outliers. However, overall the data has a good spread and there are no obvious outliers. There is no apparent trend in the variance either, suggesting that the accuracy of the data was not affected by either the changing variable of maximum load or the change from open gate to closed gate configurations. When the data for each test is displayed graphically (Figure 7), the S-N curves become apparent. There is an obvious logarithmic trend in the data. The number of cycles to failure increases logarithmically as the maximum load value decreases.

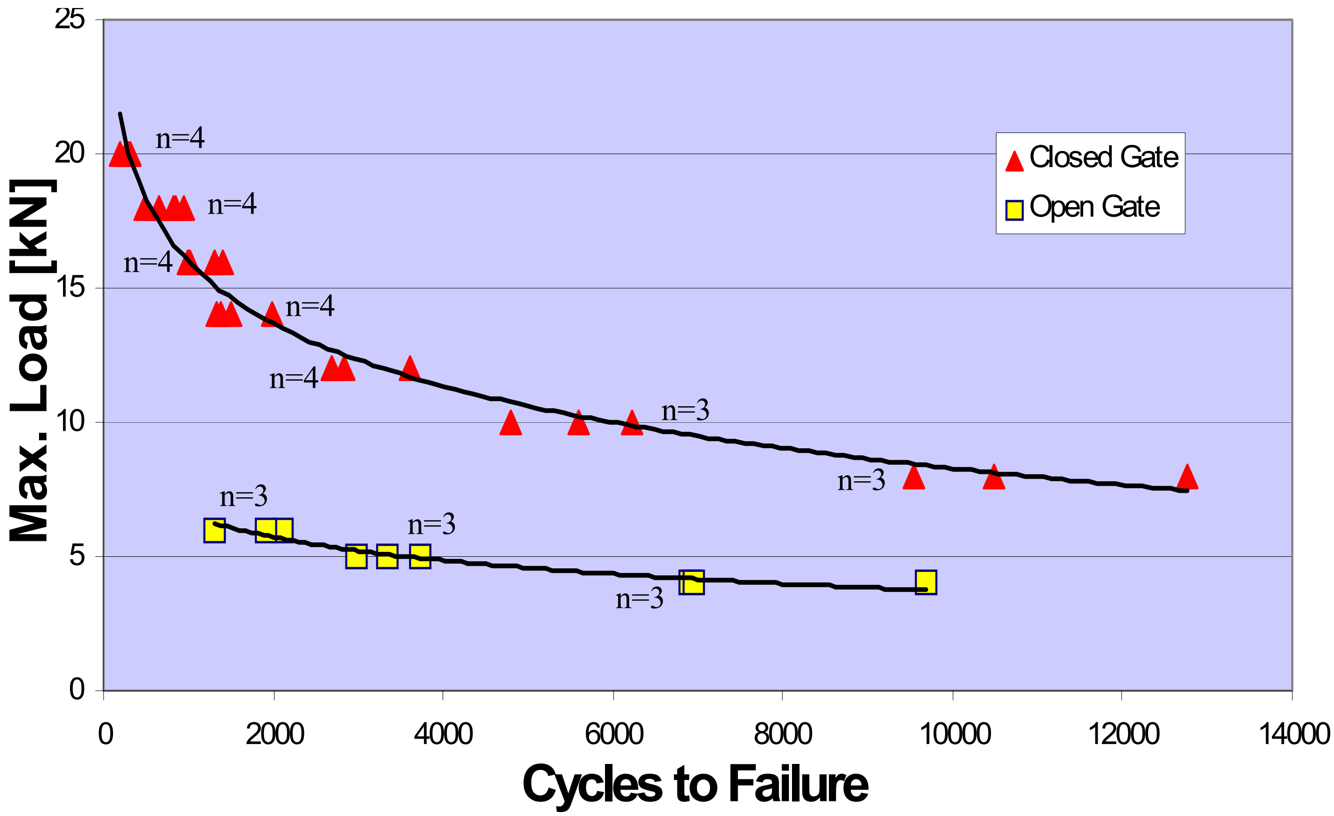

Figure 7: Graph of number of cycles to failure versus maximum load per cycle (S-N curve). A logarithmic trend line is shown for both the closed and open gate conditions. The number of points for each load value is also displayed.

As would be expected, the S-N curve for the open gate data falls well below that of the closed gate data (Figure 7), suggesting that it takes much fewer cycles to break the carabiner when its gate is open than when it is closed for the same maximum load value.

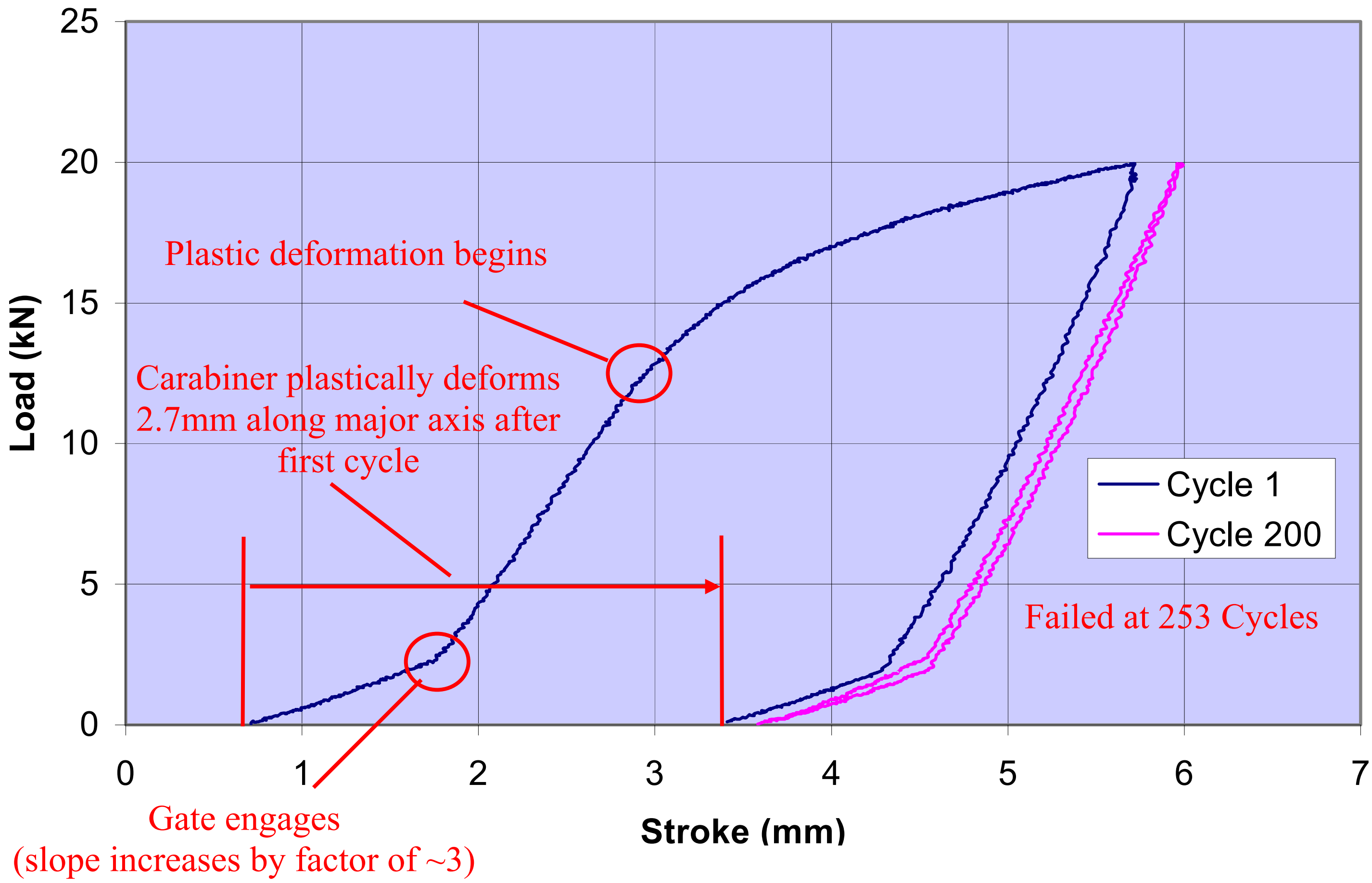

Figure 8: Graph of load versus stroke (displacement) for two cycles of a 0.5 – 20kN cyclic test. This graph displays data collected through the MTS machine for 1st and 200th cycles of the test. Ultimately, the carabiner failed at 253 cycles.

Figure 8 is a closer look at only one of the many data points displayed in Figure 7. Figure 8 shows data collected from one of the four 0.5 – 20kN cyclic tests performed. The 20kN load value is the largest load value tested in this project. As mentioned before, the 20kN value also corresponds to the worst-case scenario fall a climber could potentially take in the field. The data from the first cycle shows that a great deal of plastic deformation occurs in the first cycle. The carabiner permanently elongates by about 2.7mm. This is evident since when the carabiner returns to zero load at the end of the first cycle, the pins are 2.7mm further apart than when the carabiner was at zero load before the first cycle. The 200th cycle appears slightly displaced to the right of the end of the first cycle. This suggests that a small amount of plastic deformation occurs after the first cycle. However, it is obvious that nearly all of the plastic deformation occurs within the first cycle.

The first change in slope corresponds to the gate of the carabiner engaging at about 2kN. As the load on the carabiner is increased from zero, the gate slowly comes into contact with the gate latch, which provides added resistance against further motion. The slope increases by a factor of about three at this point. As the load continues to increase, the slope begins to drop off severely beginning at about 12kN. This change in slope indicates the beginning of plastic deformation. From this information, we know that a carabiner will experience little if no plastic deformation in its first cycle unless the load magnitude exceeds 12kN. In order to verify this, we can look at similar data collected for a lower load condition test (Figure 9).

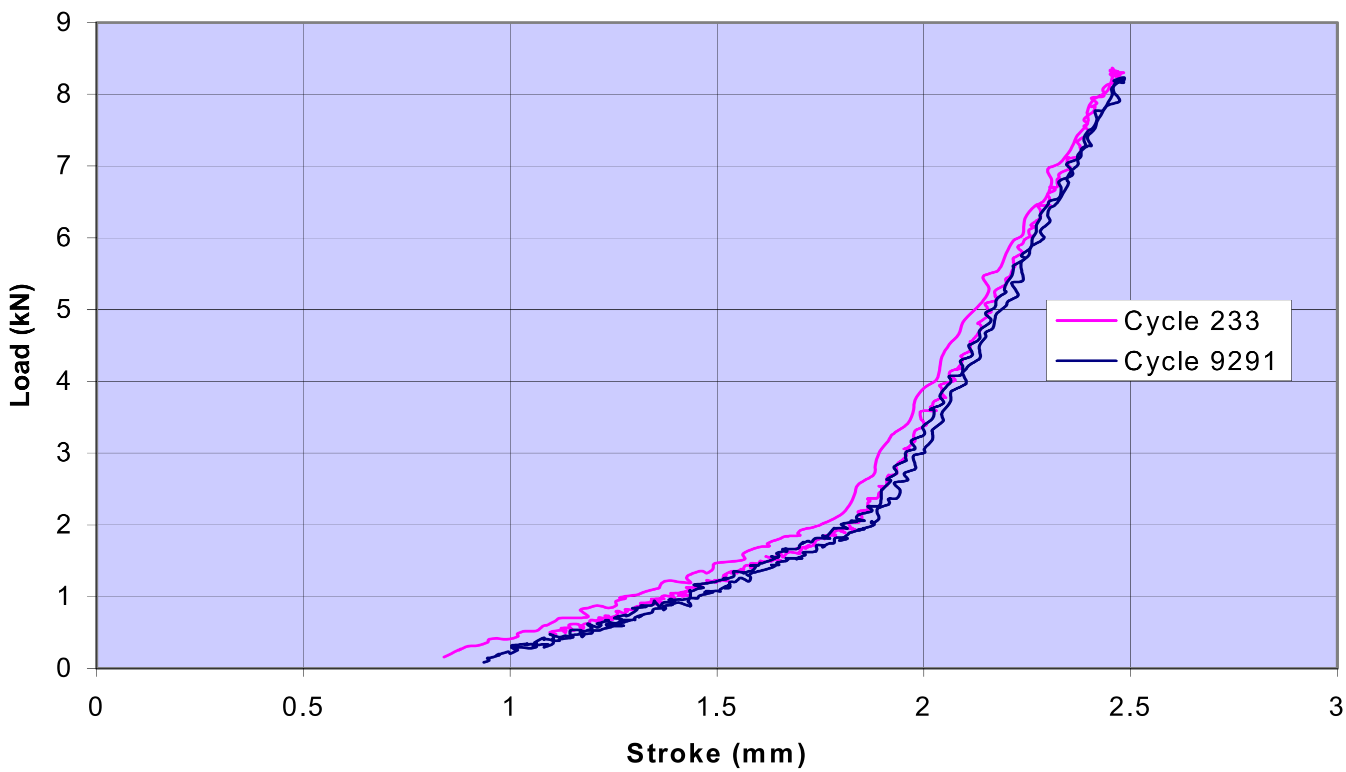

Figure 9: Graph of load versus stroke (displacement) for two cycles of a 0.5 – 8kN cyclic test. This graph displays data collected through the MTS machine for 233rd and 9291st cycles of the test.

In a 0.5 – 8kN cyclic test, the magnitude of the load never crosses the 12kN threshold for plastic deformation shown in Figure 8. However, the 9291st cycle is obviously to the right of the 233rd cycle, suggesting that a minimal amount of plastic deformation has indeed occurred despite the low load magnitudes. Again the factor three increase in slope corresponds to the gate engaging.

As mentioned before, some carabiners were outfitted with a strain gauge to measure the amount of strain in the spine of the carabiner during a cyclic test. Every carabiner that was tested broke at one of the two elbows. Therefore, the main stress concentration in a loaded carabiner is on the inside of the elbows at failure. This is where the crack forms initially. This is what was predicted by our finite element model of a "D" shaped carabiner (Figure 10).

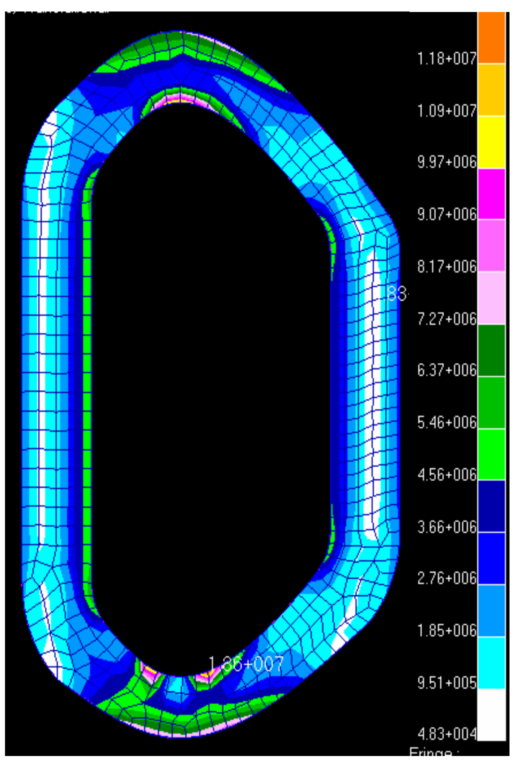

Figure 10: PATRAN Finite Element Model of "D" Shaped Carabiner showing stress concentrations on the inside of the elbows.

However, due to the shape of the carabiner at the elbow, it was impossible to place a strain gauge on the inside of the elbow to monitor the failure point of the carabiner. Instead, strain gauges were placed on the flat spine of the carabiner and still yielded interesting data (Figure 11).

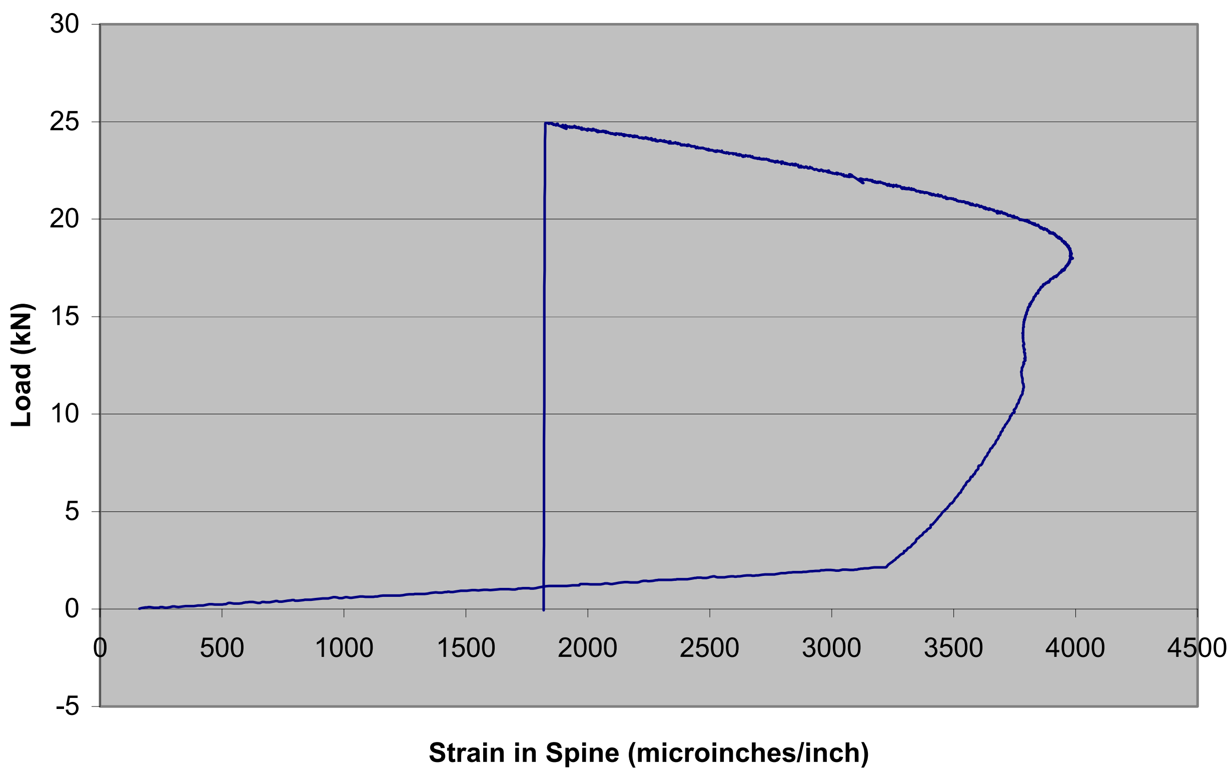

Figure 11: Graph of strain in the spine of the carabiner versus load for a single pull to failure test.

In order to display the strain in the spine for a large range of loads, a strain gauge was attached to an additional carabiner to take data on a single pull to failure test (Figure 11). As the load is increased from zero, the strain in the spine increases dramatically. Again, at about 2kN, there is a change in slope as the gate of the carabiner engages. At this point, the spine is no longer resisting the entire force of the applied load. It is now distributed over both the spine and the gate. The strain continues to increase until about 18kN, at which point it drops off dramatically even though the load is still increasing. At failure (25kN), the strain in the spine is equal to the strain at 1kN. Since the strain in the spine begins to drop within the plastic range of the carabiner, it is most likely that the shape of the carabiner changes during this time to adjust load concentrations. During the same period that Figure 11 depicts the strain in the spine decreasing, the strain in the elbows is increasing, as this is where all the carabiners eventually broke.

8.2 Crack Analysis

In addition to the number of cycles to failure and the data collected during the cyclic tests, measurements were also taken on the size of the cracks on the fracture surface of the carabiners after they had failed. Further qualitative observations of the fracture surface were also made with the use of a Zeiss Stemi 2000-C microscope system. This system provided high-resolution magnified images of the fracture surface of broken carabiners (Figure 12).

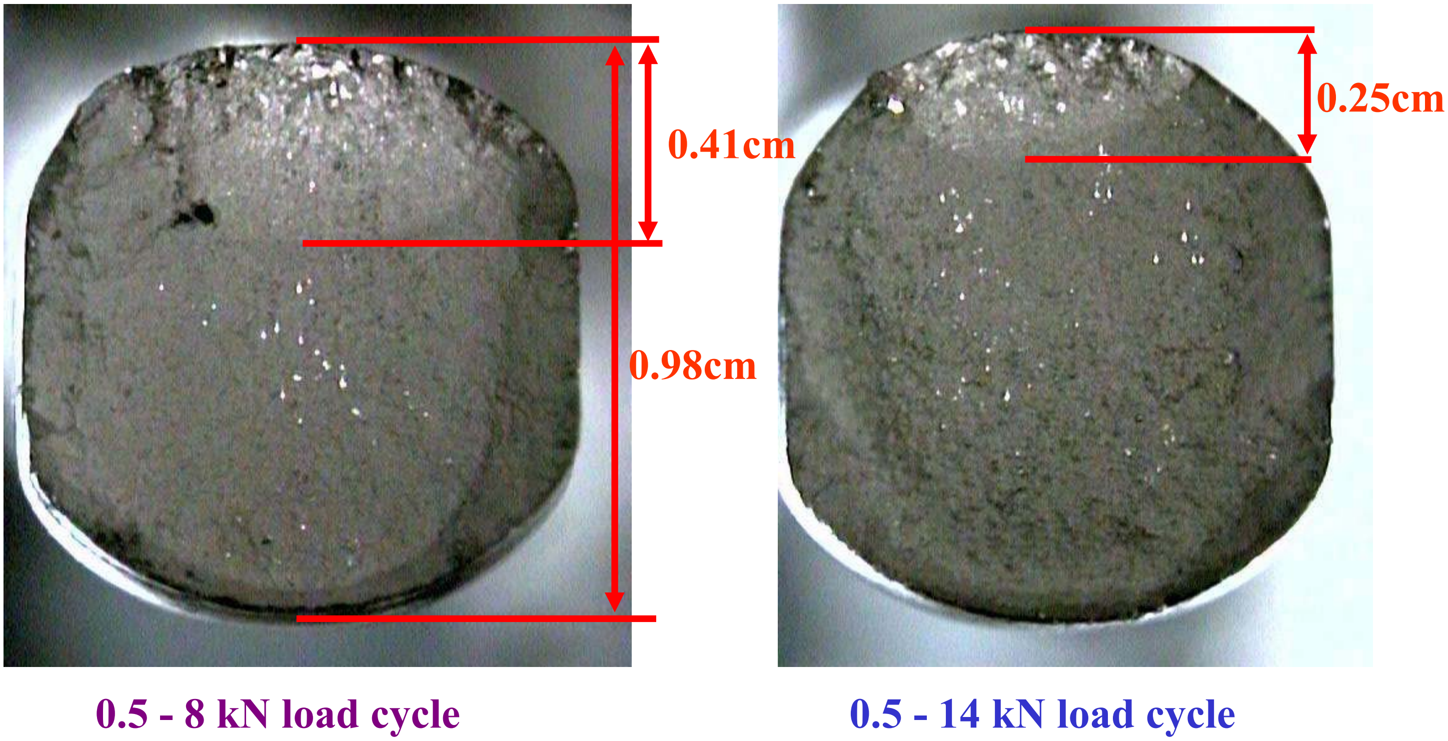

Figure 12: Photographs of the fracture surfaces of two broken carabiners displaying the difference in crack size for different load conditions. The crack extends through the lighter half moon shaped portions at the top of both pictures.

It is easy to distinguish the crack portion of the fracture surface by the color of the material. The portion of the surface that separated within the crack is smoother and hence has a lighter shade to it (Figure 12). The rest of the fracture surface is where fast fracture occurred during the final cycle. The crack propagated during an unknown number of cycles. There was no data collected on the actual propagation of cracks because a crack was never found on the surface of an unbroken carabiner despite the numerous x-rays that were taken of carabiners close to failure. The closest we came to finding a crack was when an x-ray and critical observations were taken during a 0.5 – 8kN cyclic test. The same carabiner failed less than 200 cycles later. Therefore, we only know that the crack propagates during the course of 200 cycles or less.

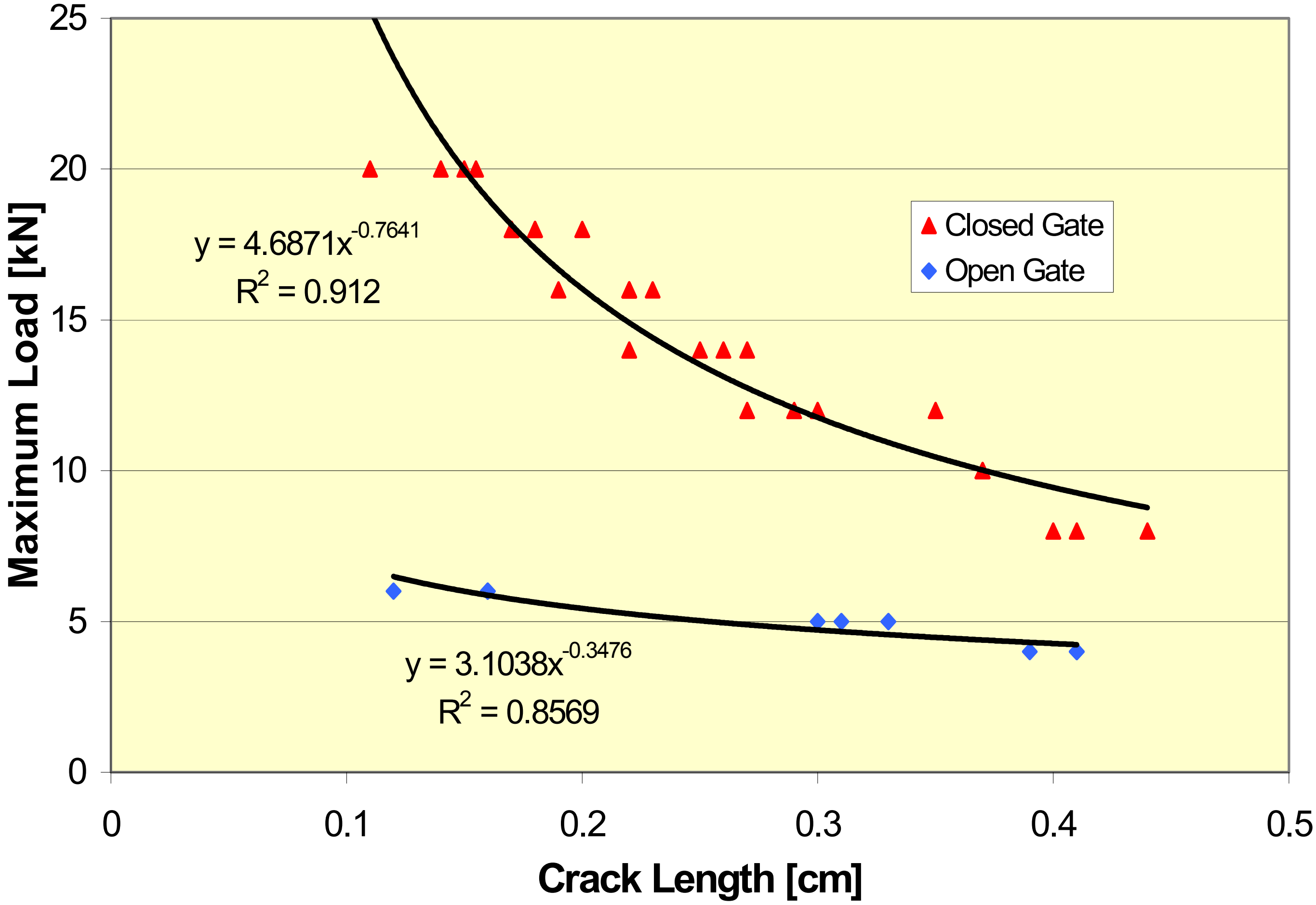

Figure 13: Graph of crack length versus maximum load. Displays data for both closed and open gate configurations. Logarithmic trend lines have been used to fit the data.

A micrometer was used to measure the length of the crack for each carabiner that was broken. The data loosely correlates to a logarithmic curve. However, there is large variance in the data suggesting that the relationship is not in fact logarithmic. Especially with the closed gate data, it is obvious that a few points lie a considerable distance from the logarithmic trend line shown. By just looking at the data points, we see that the relationship is almost linear. The general trend, however, is apparent and reliable. The crack length increases as the maximum load decreases. Propagation of a crack decreases the cross sectional area of the carabiner. Lower maximum loads have a smaller requisite cross sectional area at which fast fracture occurs. Therefore, at these lower loads, the crack is able to propagate further before catastrophic failure (fast fracture) occurs.

9 Conclusions

Even though carabiners have been known to fail in the field, such occurrences have been rare. The data collected in this project emphasizes just how rare carabiner failure in the field really is. The lifetime of the carabiners tested in this project was longer than expected. In the worst-case scenario of 20kN maximum load, the carabiner failed in excess of 250 cycles on average. That means the carabiner can normally withstand over 250 occurrences of this worst-case scenario. This indicates that carabiners have other failure modes besides just fatigue failure. Perhaps cracks form more easily on a carabiner that has been handled or knocked against a rock face if any indentations are made in the otherwise smooth surface of the carabiner.

As the results indicate that almost all the plastic deformation occurs within the first cycle that exceeds a load value of 12kN, we know that there is no consistent relationship between the number of cycles the carabiner has experienced and the amount of plastic deformation in the carabiner. The plastic deformation has either occurred or it hasn't. At best, we might be able to determine the magnitude of the maximum load the carabiner has experienced within its lifetime given an amount of plastic deformation. The measurements of the gate gap indicate the same conclusion. There is no significant increase in the size of the gate gap until after the carabiner has failed. Therefore, it is difficult to predict how much longer a used carabiner will last given a certain amount of deformation in the carabiner. As a result, we are still unable to provide the climber with the critical information he/she needs in order to make critical decisions on whether or not to retire his/her carabiner based on deformation due to fatigue.

As mentioned before, based on the observations of carabiners for cracks, we can conclude that the crack propagates relatively fast and that the carabiner therefore has a catastrophic failure shortly after the crack forms. This also indicates that the 7075 aluminum that composes the carabiner is relatively brittle.

The most notable conclusion is a proposal for a new testing method for carabiners based on the number of cycles to failure rather than the current ASTM standard based on maximum tensile strength. This meets the objective of the project by the development of a new testing standard, which provides the climber with more pertinent information of his/her carabiner. They will now know the number of cycles to failure at a variety of loads rather than the maximum tensile strength, which is often 25% greater than any load value a carabiner will experience in the field.

The new testing method employs the emulation of in-field conditions within the lab. Specifically, carabiners should be tested cyclically at load values they will experience in the field (e.g. the 8-20kN range used in this project). Also, the period of each cycle should be 0.5 seconds. As mentioned before, this is the average amount of time that a carabiner is loaded during a climber's fall. Furthermore, the load should be applied sinusoidally to reflect the dynamics of a stretching rope. The continued use of the ASTM test apparatus (i.e. the machined steel grips) is recommended. Since they are made of steel, they minimize error in displacement readings for the carabiner. The grips also allow the carabiner to rotate during cycling as it would in the field.

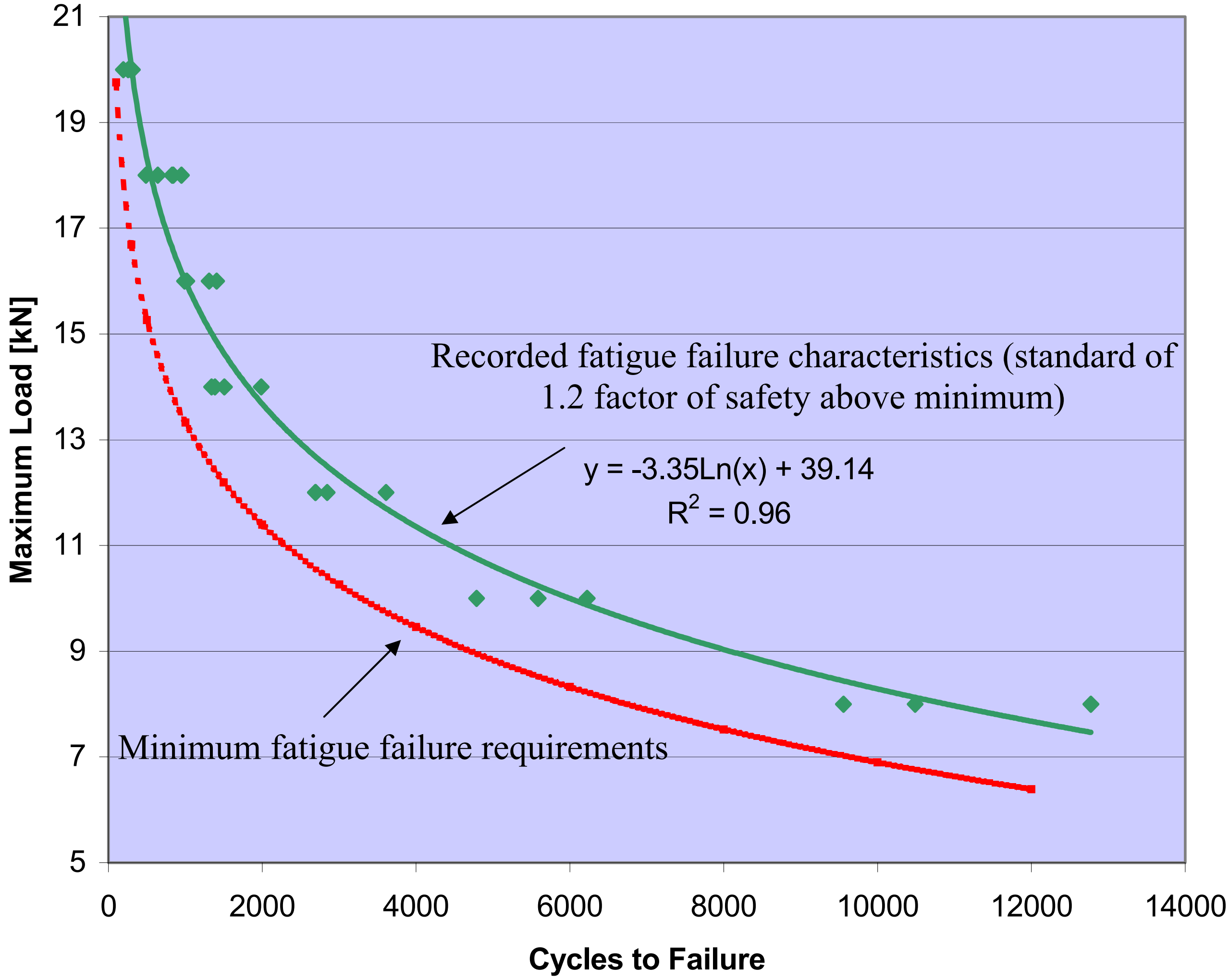

Figure 14: Graphical representation of requirements based on new proposed carabiner testing method. The red dashed line represents the minimum requirements for the carabiner tested in the project according to new method.

Figure 14 displays how the minimum requirements for a carabiner would be defined in the proposed testing method. The green trend line is the closed gate configuration data on number of cycles to failure versus maximum load. These are the same data points as were displayed in Figure 7 during the discussion of results. The trend line was displaced by a factor of safety of 1.2 to generate the minimum requirements for this carabiner. This factor of safety is the standard practice among carabiner manufacturers today. This same type of graphical representation can be generated for any carabiner that is tested in the same manner as we tested this one. The reason why this is more valuable is because it displays the minimum requirements for the carabiner in terms of number of cycles to failure. Also, the corresponding number of cycles to failure can be found for any given maximum load value.

10 Future Work

Only so much could be accomplished within the amount of time allowed for this project. Furthermore, any good experimentation project asks more questions than it answers. Many new questions arose during the course of this project that could potentially form the basis of further work.

Other failure modes could be explored in depth. It would be interesting to place notches in certain locations on the surface of the carabiner before cycling them to see how rough handling of a carabiner could result in an unusually early crack formation. We also know that carabiners do not experience the same magnitude of load for every cycle in the field. Therefore, maybe some 0.5-8kN tests could be performed after having loaded the carabiner once to 20kN in order to examine the effects of one unusually large load on carabiner lifetime.

Since every carabiner tested in this project failed at one of its two elbows, perhaps the carabiner industry should explore the feasibility of reinforcing only the elbows of the carabiner to make an overall stronger and more reliable product.

Finally, a method of predicting the remaining lifetime of a carabiner based on a given amount of deformation present in the carabiner under zero load must still be perfected in order to let the climber know when a carabiner has become unsafe to use. Potentially this could be done with an enamel coating on the metal surface of the carabiner that would crack as the carabiner became unsafe. Another possibility that should be explored is the development of a mold for carabiners that could be kept in climbing gear stores. A climber would bring his/her carabiner into the store, and if it was able to fit into the mold, it could still be deemed safe to use. One must always remember the liability issues associated with these two possible methods.

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Appendix A: Error Analysis

The largest potential source of measurement error in the testing is associated with the MTS tensile loading machine in the MIT Technology Lab for Advanced Composites (TELAC). The application of loads to a test specimen by the machine is accurate to within +/- 13N of force.[8] Therefore, the error of the MTS machine is 0.07% of the entire loading range for the largest load condition of cycling between 0.02 and 20kN. The error is 0.16% of the loading range for the low end of loads tested, which is cycling between 0.02 and 8kN. Due to the error range of the of the MTS machine, the carabiners are loaded down to 0.02kN rather than all the way to 0kN. If the MTS machine were programmed to reduce the load on the carabiner to 0kN, the carabiner may reach zero load, but even so, the load read by the MTS machine may never reduce to 0kN due to its error range. If this were to occur, the MTS machine would compress the carabiner.

For the tensile loading machine to apply loads to the carabiners in a manner that simulates the way in which carabiners are loaded by climbers, special grips (Figure 2) must be machined to fit into the vice clamps of the MTS machine. Errors in the deformation measurements of the carabiner occur if this grip deforms. Therefore, the grip is composed of steel, which has a Young's Modulus of 200GN/m^2.[12] This value is approximately three times greater than the Young's Modulus of aluminum (70GN/m^2).[12] Therefore, elastic deformation of steel is negligible within the range at which the carabiners are tested. Also, the yield strength of steel, or the force which steel may be subjected to before it plastically deforms, is 300MN/m^2,[12] which is a full four orders of magnitude greater than the maximum load for this experiment.

There are a number of additional small sources of error whose effect on the measurements is negligible and can be ignored for the purposes of this project. The strength variance of carabiners of the same design is characterized by a normal distribution. The strength rating for a particular carabiner design is determined by subtracting three standard deviations from the mean strength of the random carabiners sampled.[2] This means that due to possible manufacturing error, 0.1% of all carabiners of the same design do not meet the strength rating that their design specifies. Also, there is a small error range inherently associated with any micrometer that is used to measure plastic deformation.

Errors in strain gauge readings may have arisen from electric interference in the environment of the testing and temperature changes during testing.[13] Electric interference was accounted for by zeroing the resistance of the strain gauge in an unloaded condition by calibrating the gauge.[8] The range of normal temperature variance in TELAC is on the order of 1°C,[8] which is not sufficient to cause any measurable change in the properties of the materials being tested or in stain gauge readings.

Appendix B: Safety Concerns

Safety concerns associated with this project included the danger inherent in machining the steel grips in the Gelb Laboratory. Safety goggles were worn in the machine shop as protection against fragments of steel. Breaking carabiners using the MTS machine was another major safety concern. To prevent possible injury from flying pieces of broken carabiners, a plexi-glass encasement was placed surrounding the test section of the MTS machine. Goggles were again worn as an additional safety precaution.

Appendix C: Three-View Engineering Drawings of Grips

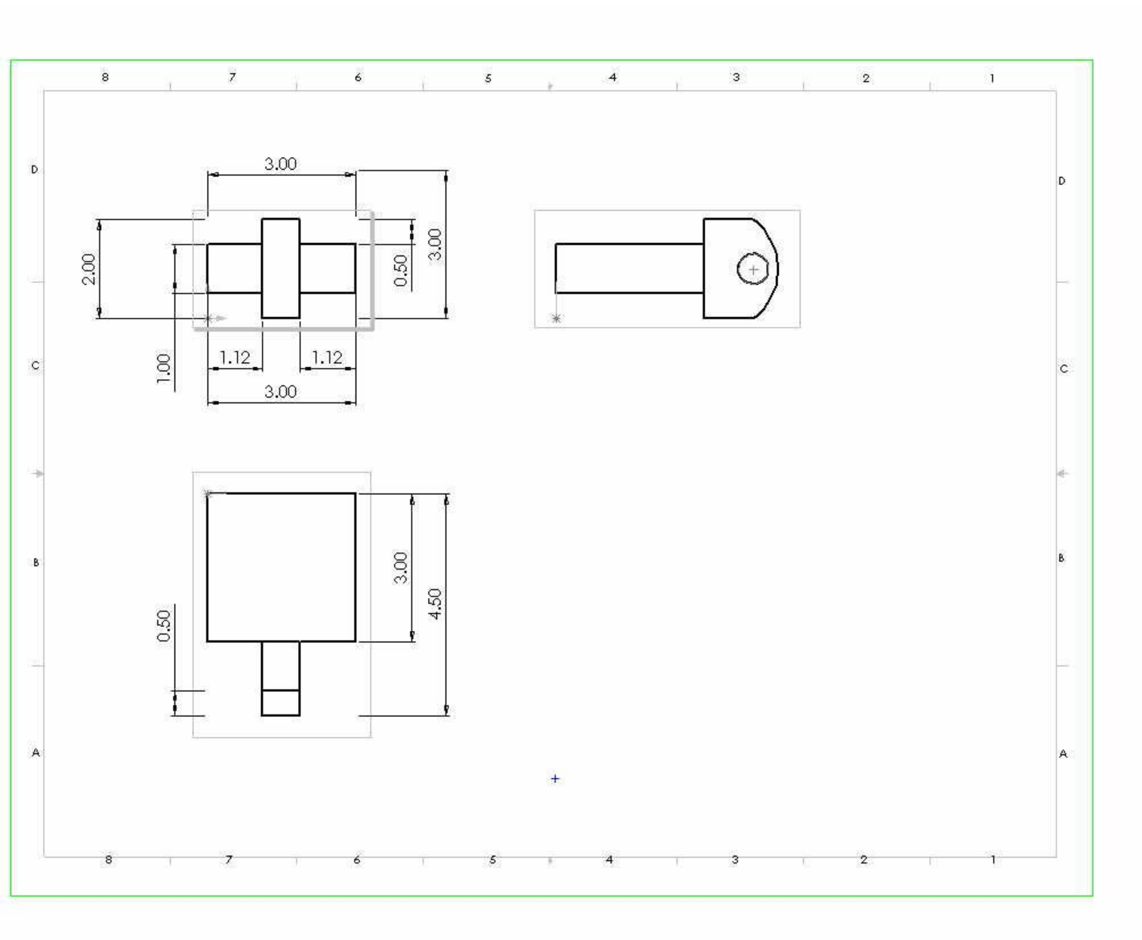

Figure 15: Three view engineering drawing and measurements of steel connecting piece that attaches grips to MTS machine vice clamp.

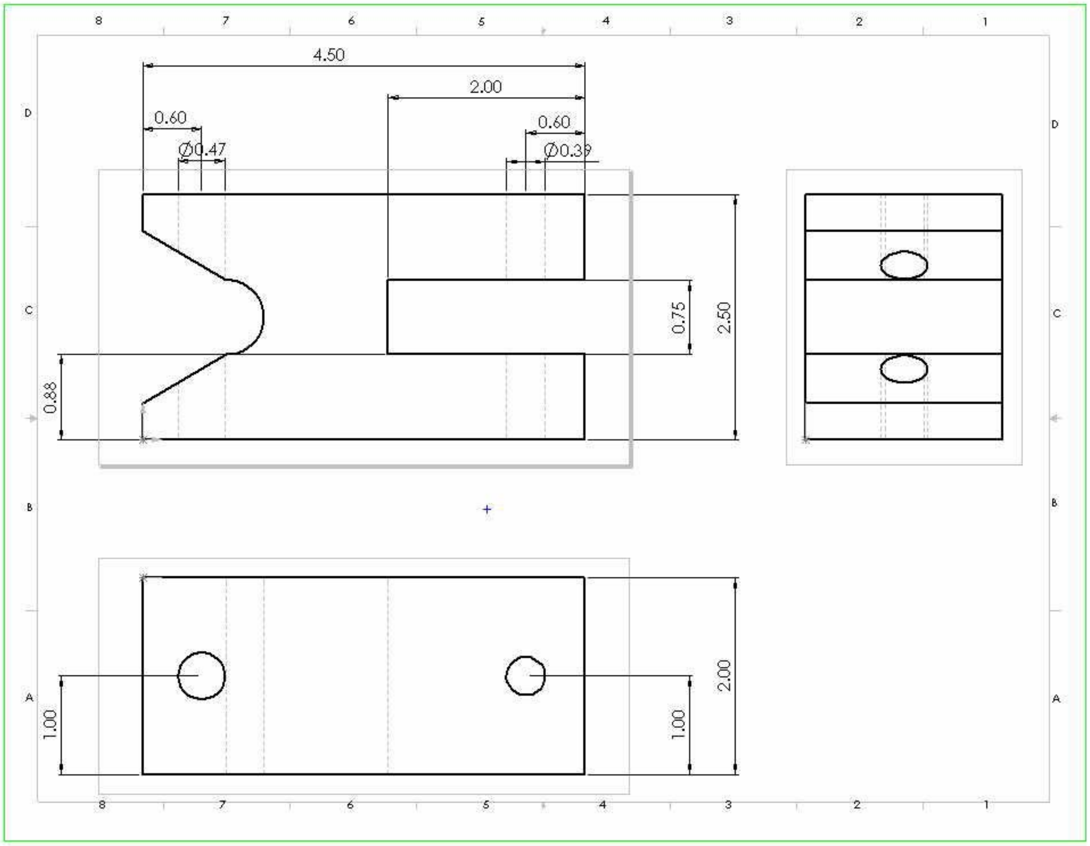

Figure 16: Three view engineering drawing and measurements of steel grip.