Fatigue Life in Damaged Carabiners

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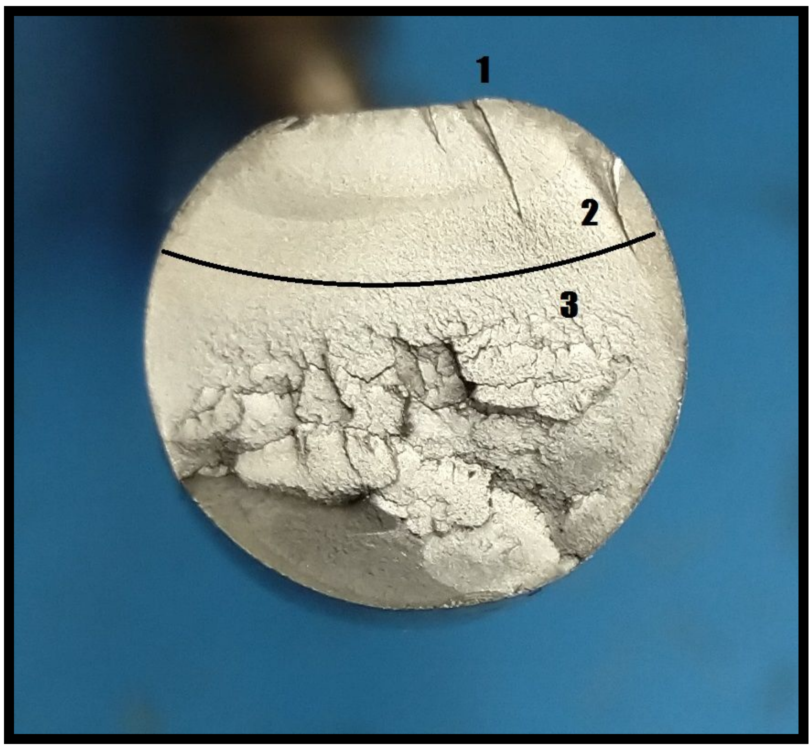
Fatigue in metals is a relatively common engineering consideration, but is not as well understood by end users of equipment, specifically in the climbing and rescue industries.

In rescue and rigging, we often consider gear strength in terms of Minimum Breaking Strength, or MBS. In reality, overloading is only one mechanism of failure. It is possible for materials to fail when loaded well below the yield point of the material, in a phenomenon known as fatigue. The basic pattern of fatigue failure in metals follows three stages. In stage 1, microcracks form in the material. Stage 2 involves microcracks progressing into macro-cracks, which cause distinctive beach marks on the fracture surface. Stage 3 is the fast fracture stage, where the remaining material cannot support the applied load, and ultimate failure occurs (Budynas, 2010).



Material selection can significantly impact fatigue life. A common descriptor is the S-N curve, which plots the applied stress against the number of cycles to failure. In steels, this curve exhibits a knee, or a stress below which the material can survive infinite cycles. Aluminum alloys do not have this knee, and will therefore fail at some number of cycles no matter the applied load. Much climbing and rigging equipment is manufactured from Aluminum alloys, so fatigue life is a characteristic of interest.

Previous published fatigue data on carabiners and climbing equipment is relatively sparse. A MIT Center for Sports Innovation study addressed fatigue failure in aluminum D-Shaped carabiners, but mostly at loads significantly above what would be considered normal rigging or climbing use. The carabiners were all new and undamaged (Blair, 2002).

Published data also exists on fatigue testing on carabiners for use in the paragliding industry. The failure mode is understood to be due to deformation in the carabiner frame before the nose contacts the gate of the carabiner. If the nose had not contacted the gate when solely bodyweight was applied, it was found that high-cycle fatigue occurred as lines fluttered during flight. Several field failures have been documented, and it was concluded that geometry of the carabiner was most responsible for the failures (Finsterwalder, 2005). Note that the geometry and loading conditions are significantly different from the rescue and rigging industry, and the high-cycle flutter conditions in flight are difficult to replicate in other practices.

The purpose of this new testing is to examine whether damage and defects have the potential to adversely impact fatigue life in carabiners, and to determine whether that adverse impact is of concern to end users.

Testing Setup

Oval-shaped auto-locking aluminum carabiners were used for this test series, as a number of cosmetic rejects were on hand. The Major Axis MBS is 23 kN, with a Minor Axis MBS of 7 kN and an open gate strength of 6 kN.

Carabiners were loaded between a ½ inch steel pin and a steel auto-locking ‘RockD ANSI’ model carabiner. The load was applied with a pneumatic cylinder controlled by a solenoid valve and PLC. Applied forces were measured with a Transducer Techniques SWO-10K load cell. The samples were cycled between 50 lbf and 1300 lbf until failure, with the cycle count measured by the PLC. After failure, each sample was collected and examined and the corresponding cycles were recorded. The 50 lbf lower force limit was used to reduce the effect of impact on the carabiners from the steel test frame. The 1300 lbf upper force limit was chosen as it is ¼ of the MBS for the selected carabiner. A one-fourth loading value is often used as a safety factor in calculating working load limits, and has been explicitly stated as the allowable in-use loading limit by at least one manufacturer[1].

Test Samples

Control - Undamaged production carabiner

Gouge in spine - Gouge created in back of spine with hammer and chisel, driven to 0.5mm deep. Gouged on both top and bottom where the frame straightens out at the spine.

Load to ½ - Loaded to ½ MBS for 3 minutes.

Load to ¾ - Loaded to ¾ MBS for 10 seconds.

[1] Kong spa - https://www.kong.it/downloads/I_KONG_CONNECTORS.pdf

Milled Groove - 3/16” groove milled 2mm into the top and bottom inside of the carabiner, simulating rope wear with small diameter rope.

2mm Notch - 45 degree angle notch filed 2mm deep into inside spine where fatigue failure commonly occurs. Worst case scenario for stress concentration.

0.5mm Notch - 45 degree angle notch filed 0.5mm deep into inside spine where fatigue failure commonly occurs.

Results

Carbiner	Mean	Variance	Reject Null?	P-Value
Control	16151	14951474	--	--
Gouge	15069	9632649	No	0.3410
Load 1/2	25637	1059968	No	0.0294
Load 3/4	34717	57693796	No	0.0036
Mill Groove	33245	74582892	No	0.0417
2mm Notch	1948	358404	Yes	0.0006
0.5mm Notch	7428	2906330	Yes	0.0036

Analysis

Fatigue life is fairly stochastic - even given controlled samples and test conditions, there exists a relatively high amount of variability in the resulting cycles to failure. In order to best interpret the data, a Student’s-T distribution was used with a single-tail two-sample unequal variance test. The Student’s-T distribution was chosen based on its use in industry and machine design on fatigue statistics (Schneider, 2003). The null hypothesis was that there was not a significantly lower number of cycles to failure between tested sample batches and the control.

The control carabiners all failed at the point in the spine where the radius of the upper or lower basket begins. In some carabiners, the material surrounding the hinge rivet on either the gate or the frame failed, though it is unknown if this happened before or after the spine failure on the final pull. It appeared to be unrelated to the either the number of cycles or the failure location, as the frame fracture surfaces were all relatively similar.

A gouge created on the outside of the carabiner with a hammer and chisel did not produce any statistically significant difference from the control sample. The carabiner broke at the same location as the control sample, in one case actually breaking slightly above the chiseled notch. This indicates that damage on the back of the carabiner may not significantly influence fatigue life, especially the location of the final fracture surface.

When loaded to ½ and ¾ MBS, carabiners actually showed statistically significant increases in fatigue life. This may be due to internal dislocations and stresses impeding crack growth. It is well documented that shot peening and pre-stressing can improve fatigue resistance (Mouritz, 2012), and these results may be due to a similar mechanism.

A milled groove simulating rope wear from a small diameter rope resulted in a statistically significant increase in fatigue life. A small diameter groove was chosen to increase stress concentration to a “worst case scenario” level. The reason for the increased fatigue life is unknown, but it is possible that the groove changed the loading geometry enough to affect the deformation of the carabiner.

A 2mm notch caused a dramatic decrease in fatigue life. The notch was filed to have a sharp corner, concentrating stress as much as possible, and was extremely deep compared to the carabiner rod diameter.

A 0.5mm notch also caused a significant decrease in fatigue life, with a difference in means of approximately 10,000 cycles. The fracture surface developed at the edge of the notch, showing plainly that it contributed to crack progression.

All fracture surfaces showed beach marks and fast fracture zones, characteristic of fatigue failure. Rupture was sudden and unexpected, with no obvious deformation or damage to the carabiner. All carabiners failed at approximately the same location as the control carabiners. Several steel carabiners broke at various points in the testing, all in similar locations to the aluminum carabiners, with evidence of fatigue damage.

Conclusions and Recommendations

Because fatigue failure is due to crack propagation, the damage is cumulative. There is no recovery over time, which should be taken into consideration with equipment inspection and retirement protocols. If carabiners are used in high-force, high-frequency rigging activities, such as slacklining, fatigue life should especially be kept in mind.

While it is difficult to predict carabiner fatigue life when new or damaged, these data suggest that certain damage may have a considerably negative effect on fatigue resistance, and that damage on the inside spine of the carabiner should be carefully considered when deciding whether to retire or not. This is not to say that other damage does not have the potential to affect fatigue life, but that damage on the inside of the spine showed a statistically significant effect in this testing.

Note that this testing loaded carabiners to forces above what most users would place on them in normal use. The magnitude of force should be considered when determining retirement protocols, and these data are not intended to serve as a guideline for when to retire carabiners, but rather to show the potential effect of damage and stress concentrators on carabiner lifetime.

A previous ITRS presentation by Garin Wallace on fatigue failure in steel frame rappel racks stressed the importance of inspection and retirement of gear. This advice is obviously applicable to aluminum carabiners as well, and should be kept in mind as teams refine and apply protocols.

All testing was performed in a lab under controlled conditions. As always, use these data and analyses at your own risk. Follow manufacturer recommendations and guidelines for equipment use.

Data

Sample Tested	Cycles to Failure				
Control	22504	13309	16900	13090	14952
Gouge in Spine	11756	17909	15542		
Load to 1/2	26365	24909			
Load to 3/4	33742	27657	42754		
Milled Groove	23687	35561	40487		
2mm Notch	1474	1750	2621		
0.5mm Notch	5462	8492	8331		

Bibliography

Schneider, C. R. A., & S. J. Maddox. (2003). *Best practice guide on statistical analysis of fatigue data* . International Institute of Welding

Budynas, R. G., & Nisbett, J. K. (2010). *Shigley's mechanical engineering design* (9th ed.).

Faires, V. M. (1965). *Design of machine elements* (4th ed.). New York: Macmillan.

Mouritz, A. P. (2012). *Introduction to aerospace materials*. Reston, VA: American Institute of Aeronautics and Astronautics.

Blair K, et al. (2002). *Analysis of fatigue failure in D-shaped carabiners.* Massachusetts Institute of Technology Center for Sports Innovation.

Finsterwalder, T. (2005). *Karabiner problems – DHV hearing of karabiner manufacturers.* http://finsterwalder-charly.de/images/stories/startseite/downloads/karabinertest_april05_eng.pdf

Wallace, G. (2009). *High cycle fatigue testing.* Proceedings of the International Technical Rescue Symposium.