Analysis of fatigue failure in D-shaped karabiners

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Abstract

In order to determine the response of aluminum karabiners to cyclic loading, a single type of karabiner (cold forged, D shape, weight 50 g, 7075 aluminum) was cycled to failure under a range of conditions. Deformations were recorded continuously by the testing machine and verified by manual measurement of the karabiner and an uncalibrated strain gauge affixed to the karabiner spine. Internal crack growth was monitored by taking long-exposure X-ray photos of the karabiners near the end of their lifetimes; after failure, the crack surface area was recorded. The load/life (*L/N*) curve is $L_C = 85.4\ (N_C)^{-0.25}$ for the closed-gate condition and $L_O = 39.3\ (N_O)^{-0.25}$ for the open-gate condition. Deformation occurs only at loads above 12 kN and all measurable deformation occurs in the first three cycles of loading. Crack growth was never observed before failure; crack size is consistent with expectations but the asymmetrical karabiner geometry makes it difficult to compare this data to standards. These results suggest an *L/N* curve can be used to characterise karabiner lifetime.

Keywords: fatigue failure, karabiner

Introduction

Current karabiner strength standards (UIAA, 2004) are single pull to failure (SPTF) measurements that do not represent the cyclic loads applied to karabiners under normal climbing conditions in which they are subject to repeated loading due to falling, hanging and lowering. The resulting forces vary in magnitude from approximately 1 kN to 20 kN. Only the most severe falls produce loads close to the minimum SPTF rating (24 kN); most loads are in the 1 kN to 10 kN range (Pavier, 1998; Maegdefrau, 1989). Cycling at even these relatively low forces eventually leads to the failure of an aluminum karabiner through microcrack propagation. This fatigue lifetime is of concern to the climbing community because climbers must evaluate karabiner purchases, monitor karabiner use, and determine when to retire karabiners. Current karabiner retirement guidelines address only visible damage, wear and extreme falls; fatigue lifetime remains unaddressed. This study characterises the lifetime of karabiners under cyclic loads that reflect their in-field use.

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Background: climbing loads

A number of models and empirical studies predict the load and load duration to which karabiners are subject in climbing use (Pavier, 1998; Maegdefrau, 1989).

Such work indicates close correlation between empirical measurement and the forces predicted by both the analytic model and computer simulation. The single cycle period (0.5 seconds) chosen in this work is in the middle of the load duration range. The forces used in this study (4 kN to 20 kN) correspond to the middle range and high end of predicted forces. It is assumed that the lowest forces are unlikely to pose a danger to climbers and that measuring fatigue lifetime at these low forces is prohibitively time consuming. Choosing the high end of the force range yields worst-case results.

Methods

Overview

All tests used a single type of karabiner, an example of a popular, generic karabiner (Fig. 1). It is D-shaped, with a spine cross section of 1 cm × 0.84 cm, made of 7075 aluminum, cold forged, and has SPTF ratings of 24 kN (closed gate) and 7 kN (open gate); each karabiner was loaded with a single 12 kN proof-load cycle as part of the manufacturing process.

Thirty-five karabiners were sinusoidally cycled to failure under different peak loads; the cycle period was 0.5 seconds for all tests. At loads above the minimum open-gate strength, karabiners were loaded with the gate closed; at loads below the minimum open-gate strength, karabiners were loaded with the gate held open.

Karabiner deformation was monitored by taking X-ray pictures, recording displacement data collected directly from the tensile testing machine, and measuring both karabiner length and gate gap, and monitoring a strain gauge affixed to the karabiner spine.

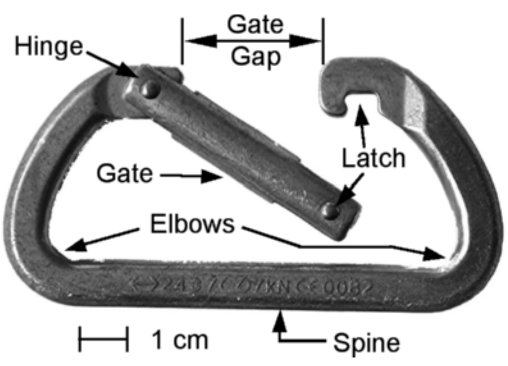

Figure 1 Karabiner used in this study with parts labelled

Finally, karabiners were tested both prior to and after failure for crack growth by taking X-ray pictures. After failure, the size of the crack was measured on the failure surface.

Test apparatus

Fig. 2 depicts the test fixture, which meets ASTM F 1774 (ASTM). Each end of the karabiner was clipped over a steel dowel with a 5 ± 0.05 mm radius. Each dowel was attached to a steel grip, which was in turn pinned to a connector piece that allowed the entire assembly to be clamped to the tensile testing machine.

The tensile testing machine applied the cyclic, dynamic loading to the karabiners. A computer recorded the displacement, load and time data. Load measurements were accurate to 0.16%, and displacement to 0.33%. The X-ray pictures were taken on a Torrex 150D X-ray machine, and the microscopic pictures of the karabiner fracture surface were taken on a Zeiss Stemi 2000-C stereo microscope.

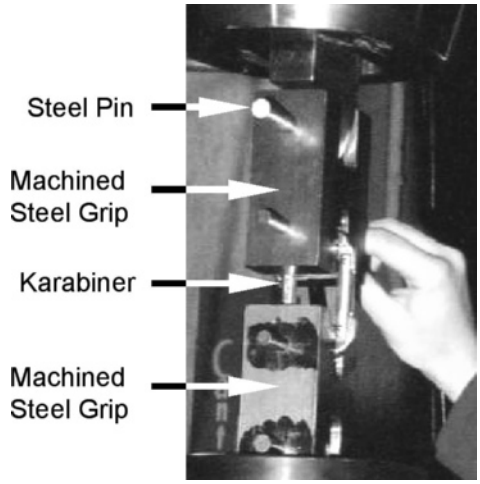

Figure 2 Photograph of test fixture. The fixture meets ASTM specification F 1774

Experimental approach

Karabiners were cycled to failure under both open and closed-gate conditions at the upper end of their load range, specifically from 8 kN to 20 kN for closed-gate and from 4 kN to 6 kN for open-gate conditions. The minimum load in the cycle for all cases was 0.5 kN. Using a non-zero, but small minimum load was necessary to ensure the karabiner remained in alignment in the testing rig and was not jerked at any point in the load cycle. For example, in the 20 kN case, the karabiner was cycled continuously between 0.5 kN to 20 kN to 0.5 kN in 0.5 seconds. The final test matrix is shown in Table 1. For each case, the number of cycles to failure was recorded.

Table 1 The test matrix: a total of 35 karabiners were tested, 9 in the open-gate configuration and 26 in the closed-gate configuration

	Cyclic load range (kN)	Number tested
Open gate	0.5–4	3
	0.5–5	3
	0.5–6	3
Closed gate	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

The deformation of the karabiner was measured in four ways.

- The tensile testing machine recorded the displacement of the bottom clamp. Since the top clamp remained fixed for all tests, this displacement represents the karabiner's deformation.
- For the 8 kN and 20 kN tests, a strain gauge was affixed to the outside of the karabiner's spine and displacement data was continuously recorded. Because the strain gauge was not calibrated, the resulting data is only qualitative.
- The length of the gate gap (Fig. 1) was periodically measured with a micrometer to determine if the karabiner deformation could be observed by a change in the gate gap size.
- Finally, short-exposure X-ray pictures were taken at intervals during 8 kN, 10 kN, and 12 kN tests. The images were copied onto transparencies and placed on top of each other to determine whether any discernable deformation occured during cycling.

Results

Overview

These results characterise the relationship between load and the number of cycles to failure (*L/N* curve). The most surprising result is the observation that most deformation occurs within the first cycles of loading rather than progressing throughout the lifetime. The net deformation is so small that it is hardly, if at all, visible to the naked human eye even when comparing superimposed X-ray photographs from different cycles. No surface cracks were observed by X-ray photography during cycling, but post-failure analysis of the fracture surface yielded results concerning the critical crack size of the karabiners.

Cyclic failure

The results for the maximum load against cycles to failure are shown in the graph in Fig. 3. *L/N* curves are typically characterised using power curve fits. Equations 1 and 2 are the resulting fits for this data. ($R^2 > 0.9$ for both cases.)

$$L_C = 85.4\,(N_C)^{-0.25} \tag{1}$$

$$L_O = 39.3\,(N_O)^{-0.25} \tag{2}$$

Here, L_C and N_C are defined to be the maximum applied load and the resulting number of cycles to failure for the closed-gate case. Similarly, L_O and N_O are defined as the maximum applied load and the resulting number of cycles to failure for the open-gate case.

Table 2 provides an overview of the variance data. The percentage variation displayed in the far right column is 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.

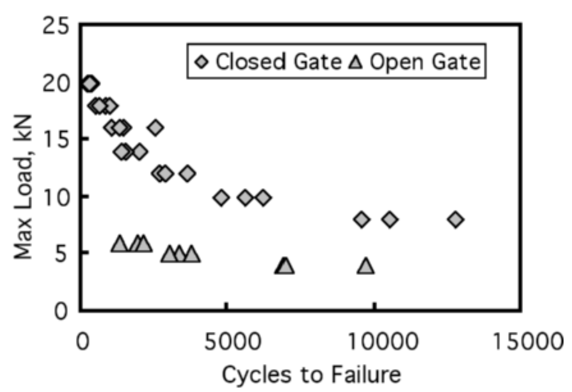

Figure 3 Load versus cycles to failure results for closed-gate and open-gate testing

There is an indication of an outlier in the 16 kN case; however, for the purposes of this study, this has not been investigated further. The lack of an apparent trend in the variance suggests that the accuracy of the data is not affected by either the changing variable of maximum load or the change from open-gate to closed-gate configurations.

Table 2 Standard deviation and variance data for each load condition

	Cyclic load range (kN)	Mean cycles to failure	Standard deviation	Variation (%)
	0.5–4	7849	1598	20%
Open gate	0.5–5	3350	384	11%
	0.5–6	1774	413	23%
	0.5–8	10939	1657	15%
	0.5–10	5533	722	13%
	0.5–12	2958	439	15%
Closed gate	0.5–14	1556	297	19%
	0.5–16	1451	209	43%
	0.5–18	750	200	24%
	0.5–20	263	51	20%

Deformation

Gate gap measurement and overlaid X-ray photographs both failed to detect deformation. Careful measurement of karabiner length shows small deformation (approximately 2 mm) for loads above 20 kN. The deformation data collected from the tensile testing machine shows that most karabiner deformation at higher loads occurs within the first cycles of loading. Fig. 4 shows this behaviour for a cyclic test at 20 kN. The 1st and 200th cycles are shown for comparison.

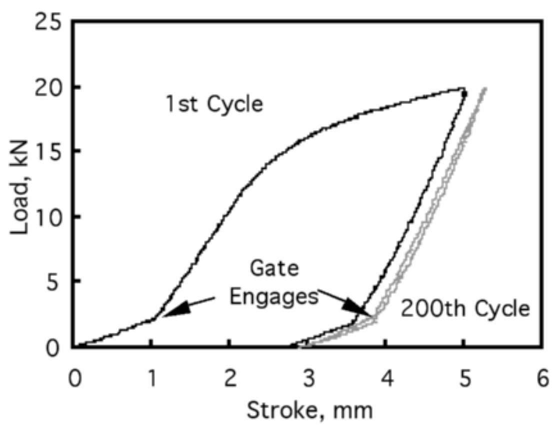

Figure 4 Load/stroke plot for two cycles of a 20 kN loading test

For lower load cycles, karabiners experience nearly elastic behaviour throughout their lifetime. Fig. 5 depicts the difference in stroke between cycle 233 and cycle 9291 of an 8 kN test.

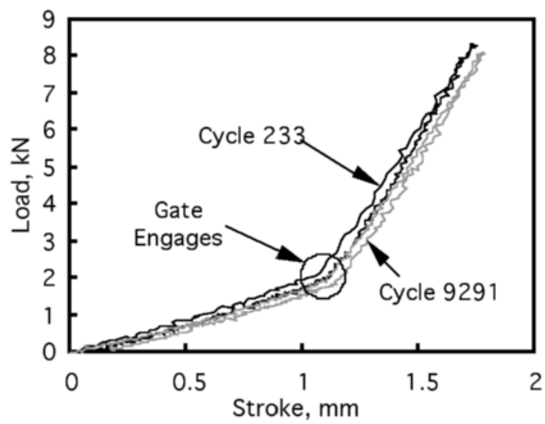

Figure 5 Load/stroke plot for two cycles of a 8 kN loading test

The strain gauge data collected from the spines of karabiners confirm tensile test results: plastic deformation during the initial loading above loads higher than half of the karabiner's rated strength, and nearly elastic deformation under all other loading conditions. The results for the 20 kN and 8 kN cases are shown in Figs. 6 and 7. Fig. 6 also shows the decrease in strain along the karabiner spine at loads above approximately 8 kN. This strain decrease suggests a subtle change in the karabiner geometry. The resulting elongation produces the observed reduction of the strain in the spine with increasing load.

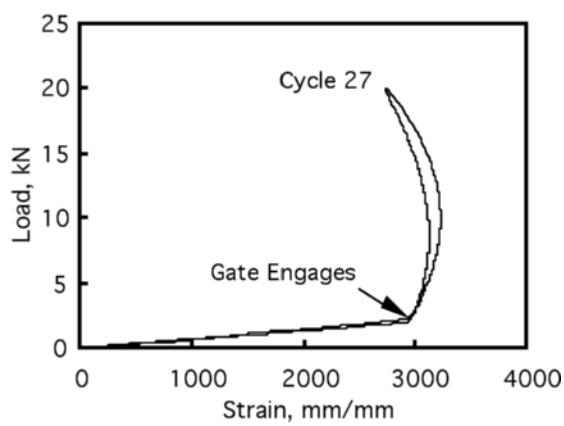

Figure 6 Load/spine strain plot for one cycle of a 20 kN loading test

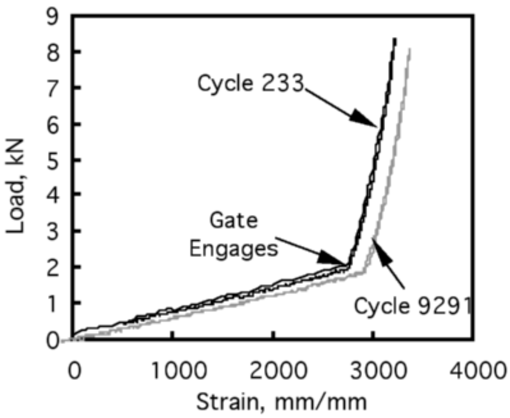

Figure 7 Load/spine strain plot for two cycles of a 8 kN loading test

Fatigue crack growth

Karabiners cycled at 8 kN were periodically X-rayed to observe surface crack formation. Because the exact lifetime of a karabiner cannot be predicted, karabiners were X-rayed approximately every 500 cycles until failure. No X-rays indicate cracks. The X-ray taken within the smallest number of cycles prior to failure (197 cycles) does not show any visible cracks.

Despite this inability to observe cracks before failure, the fracture surface provides a clear indication of the crack growth. Two pictures of these fracture surfaces are shown in Figs. 8a and 8b. The crack surface is the lighter half-moon shaped area, which is polished by the repeated loading. It is clear that the lower loading condition results in the crack propagating over a longer number of cycles.

The crack length, the width of the crack surface, for each broken karabiner was determined using a micrometer. The relationship between crack length and load is shown in Fig. 9.

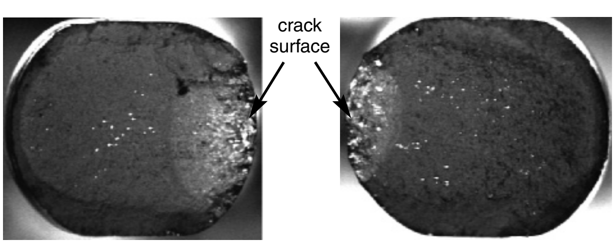

Figure 8 Fracture surface photographs for (a) an 8 kN loading test, and (b) a 14 kN loading test. The karabiner cross-section is 1 cm × 0.8 cm. The crack initiates from the inside of the karabiner. The crack surface is the light oval patch

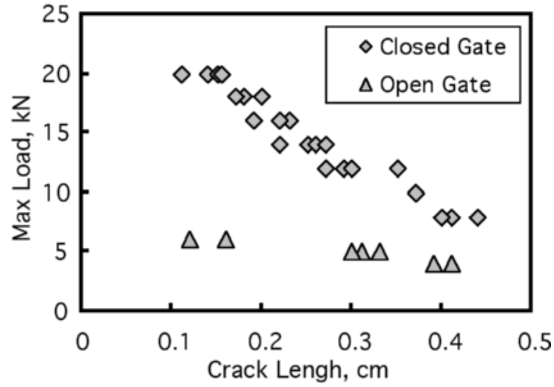

Figure 9 Crack length measured from the fracture surface for each loading condition

All karabiners fractured in the same place, with the crack initiating on the inside where the spine begins to curve (Figure 10). Fractures occurred at both the latch and hinge ends of the karabiner; the fracture end had no correlation to the karabiner's orientation in the clamp fixture.

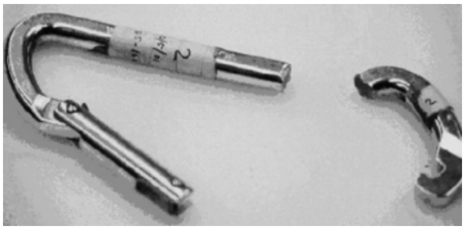

Figure 10 Fracture location typical for all test cases

Discussion

Cyclic testing

Fatigue results show that even at loads representing extreme climbing falls, this specific type of karabiner lasts a long time. The shortest lifetime, 194 cycles, occurred at 20 kN. Presumably, at this load, the climber would require spinal surgery long before karabiner retirement was necessary. This result should be very encouraging to climbers, because 20 kN falls are a worst-case condition that should not occur in normal use.

Deformation

Karabiner deformation was quite small. Under loading conditions above half of the karabiner's rated strength, a 2.0 mm increase in karabiner length occured. Under less severe loading, no deformation is discernible.

When deformation does occur, most of the deformation occurs in the first few cycles of loading, suggesting that the aluminum becomes work-hardened in these first few cycles. Further testing must be carried out to support this hypothesis.

These general trends in the deformation of karabiners suggest that karabiner failure cannot be predicted by the deformation characteristics observed in this study.

Fatigue crack growth

Long-exposure X-ray photographs (0.03 mm resolution) taken to monitor crack formation show no signs of crack growth at the surface up to 197 cycles before failure. One cannot take an X-ray photograph normal to the crack initiation surface, as the crack initiates at the inside elbow of the Karabiner. Thus, it is unclear whether the crack initiates, propagates and fails within a very few cycles, or whether the angle of the X-ray photograph does not allow for earlier detection.

The relationship between crack length and load is consistent with the theoretical model (Fuchs, 1980), but the non-standard geometry of the karabiner prohibits any direct comparison.

Conclusions

Development of a fatigue standard

The effects of cyclic loading on a karabiner can be characterised by the *L/N* curve that can be measured easily and accurately. The resulting *L/N* curve provides a quantitative measure of karabiner lifetime, a measure that is otherwise unavailable. If the single karabiner model tested in this study is an indicator of general karabiner performance, most karabiners would exceed the specifications of a reasonable *L/N* based lifetime standard. We predict that this lifetime will become increasingly more relevant and difficult to meet as karabiners become increasingly lighter.

Deformation as a measure of lifetime

Detection of deformation cannot be used to predict karabiner failure. It was found that deformation of karabiners was almost undetectable. At best, detection of slight deformation can be used to determine whether a karabiner has been subjected to a significant load of over half of the rated strength.

Future work

Further studies of cyclic testing would include testing numerous other karabiner models, determining the effects of variable amplitude loading patterns that mirror climbing practices better than constant amplitude loading, and combining cyclic loading with other use factors such as oxidation and nicking. Additional effort should be devoted to simplifying cyclic lifetime testing so that tests can be performed easily and the results can be clearly conveyed and interpreted. For example, the number of cycles to failure at half the maximum strength rating might serve well as an indication of karabiner fatigue lifetime.

The cyclic testing of numerous karabiner models would satisfy two objectives: characterisation of the individual karabiner models and characterisation of karabiner types. Our deformation results suggest that karabiners undergo plastic deformation, resulting in subtle changes in geometry. These effects may differentially influence the fatigue lifetime of karabiners of differing geometries and constructions such as those indicated in Table 3. The cyclic lifetime of karabiner models is of immediate interest to climbers.

Table 3 Karabiner design parameters that could affect the fatigue life.

Karabiner design parameters

Gate design	Latch type	Shape	Forging	Weight	Anodised
Wire gate	Pin and latch	D	Hot forged	Light	Yes
Non-wire gate	Dovetail karabiner	Oval	Cold forged	Normal	No
Bent gate		Offset D		Heavy	
		Pear			

While cyclic loading with a single force is a better measure of climbing loads than SPTF, climbing loads vary substantially. Further work would characterise typical load distributions, subject karabiners to these distribution patterns, and compare the distribution results to the results from the constant amplitude load case. Finally, cyclic load testing can be combined with oxidation or nicking, processes that karabiners are subject to that may affect strength and crack propagation properties.

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