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What Determines the Strength of Climbing Karabiners?

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ABSTRACT

This paper examines what determines the methods of failure and hence strength of climbing karabiners. First experiments were carried out on karabiners under simulated climbing conditions in both open and closed gate situations. A discrepancy was found between the load at break of the karabiners in the tests and their rating. A British Standard test was then carried out. Next a simple finite element model was created and the point of maximum stress compared to the point of failure on the test karabiners. Finally an accurate finite element model was created and compared to the results from one of the experiments. Many insights were gained into the causes of failure of karabiners which will lead to future research.

Nomenclature

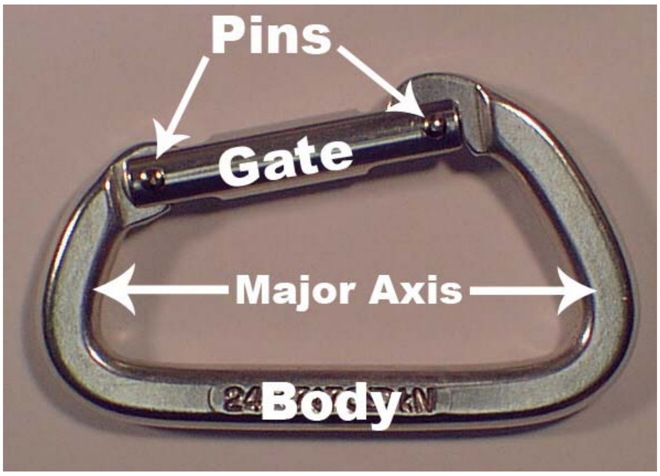

Figure 1

KB1 – HB Wales Standard 10mm Snap Straight Gate

KB2 – HB Wales Standard 10mm Snap Bent Gate

KB3 – Mountain Technology 10mm Snap Straight Gate MT151

KB4 – Mountain Technology 10mm Snap Bent Gate MT153

KB5 – DMM Tru Screw Locking Straight Gate A182

Troll – Troll 20mm wide x 60cm Long Flat Sling

MT – Mountain Technology 20mm Wide x 26cm Long Flat Sling MT156

Bar – 12mm Diameter machined steel bar.

c – Indicates the gate was closed.

o – Indicates the gate was open.

ABS – Absolute

All units in SI unless otherwise stated.

1. Introduction

1.1 Project Aims

Experimental Aims

- To establish the failure modes of karabiners under longitudinal loading.
- To compare the load at failure to the rating on the karabiners.
- To compare realistic and British Standard testing methods.

Finite Element Analysis Aims

- To compare the observed failure modes with likely failure modes calculated from FEA.
- To construct a detailed model and attempt to validate it against the data recorded from the experiments.

1.2 What is a Climbing Karabiner?

Simply a karabiner is an approximately d-shaped section of metal with a spring loaded closing bar used as a link to connect elements of climbing equipment. They have many uses in both the sport and industrial safety markets however for the purposes of this thesis only sport climbing karabiners will be considered.

1.3 Types of Karabiners

Body Shape

However the most common shape for general purpose climbing is the "asymmetric D-shape" or "off-set D-shape". There are however some more exotic variations on the above design. In this project 4 asymmetric D-shaped karabiners and one exotic asymmetric D-shaped karabiner will be considered.

Body Cross-Section

The most common cross-section is a simple round or oval section, this is easy to manufacture and allows excellent rope movement through the karabiner. This section is used in the HB Wales Karabiners and can be seen in Figure 2.1.1.

Another common cross-section is the "t-shape" this is because in major axis loading the highest stresses are experienced on the inner surface of the karabiner body. This section is used in both the Mountain Technology and DMM karabiners and can be seen in Figure 2.1.3.

In this project 2 round and 3 t-shaped karabiners will be considered as they are the most common.

Gate Shape

Straight Gate, is the most common and consists of a cylindrical rod with 2 stainless steel rivets through it that joins across the opening. This shape of gate is used by all of the above manufacturers. The other common shape is Bent

Gate, the bent shape makes it easier to clip rope through and these karabiners are usually found at one end of a quickdraw extender. These shapes of gates are used on both Mountain Technology and HB Wales karabiners.

Closing Mechanism

The simplest closing mechanism used in karabiners is a Snap Gate, in this style the gate simply snaps back into place. While this makes the karabiner quicker and more convenient to use it does mean that the gate can accidentally pop open. This style of gate is used on the Mountain Technology and HB Wales karabiners.

The other style of closure mechanism is a Locking Gate, in this style a device is used to lock the gate closed in place thus preventing accidental opening. The most common type of locking gate is the Screw Gate where a sleeve is screwed back and forward along the length of the gate to lock over the free end of the karabiner. There are quicker or more secure types of locking gates however these are normally patented and hence a type is normally only used by one manufacturer.

1.4 Materials And Manufacture

Materials

As this project is focusing on climbing karabiners weight is almost always a concern so the now very common aluminium karabiner will be considered. The exact alloy's are normally closely guarded by karabiner manufacturers but it is widely accepted that the most common aluminium alloy used is 7075. **[1]**

Manufacture

The most common method of manufacturing high performance aluminium karabiners is through the process of Hot Forging followed by quenching and ageing heat treatment. This gives better resultant material properties than for example casting. **[1]**

1.5 British/European Standards

Karabiner Standards

The most recent British and European Standards were set in 1998 under "BS/EN12275 Mountaineering Equipment. Connectors, Safety Requirements and Test Methods". **[2]**

This standard specifies, among other things, the minimum tensile strengths for karabiners under different loading situations and prescribed testing methods.

Minimum Tensile Breaking Load along Major Axis	20kN
Minimum Tensile Breaking Load along Minor Axis	7kN
Minimum Tensile Breaking Load Open Gate	7kN

The testing method specified for measuring the tensile strength for loading along the major axis with both open and closed gates is:

Load the karabiner using 12mm diameter steel bars and separate the bars with a crosshead speed of 20-50mm/minute until the karabiner fails.

2. Experiments

2.1 Testing Apparatus

Karabiners

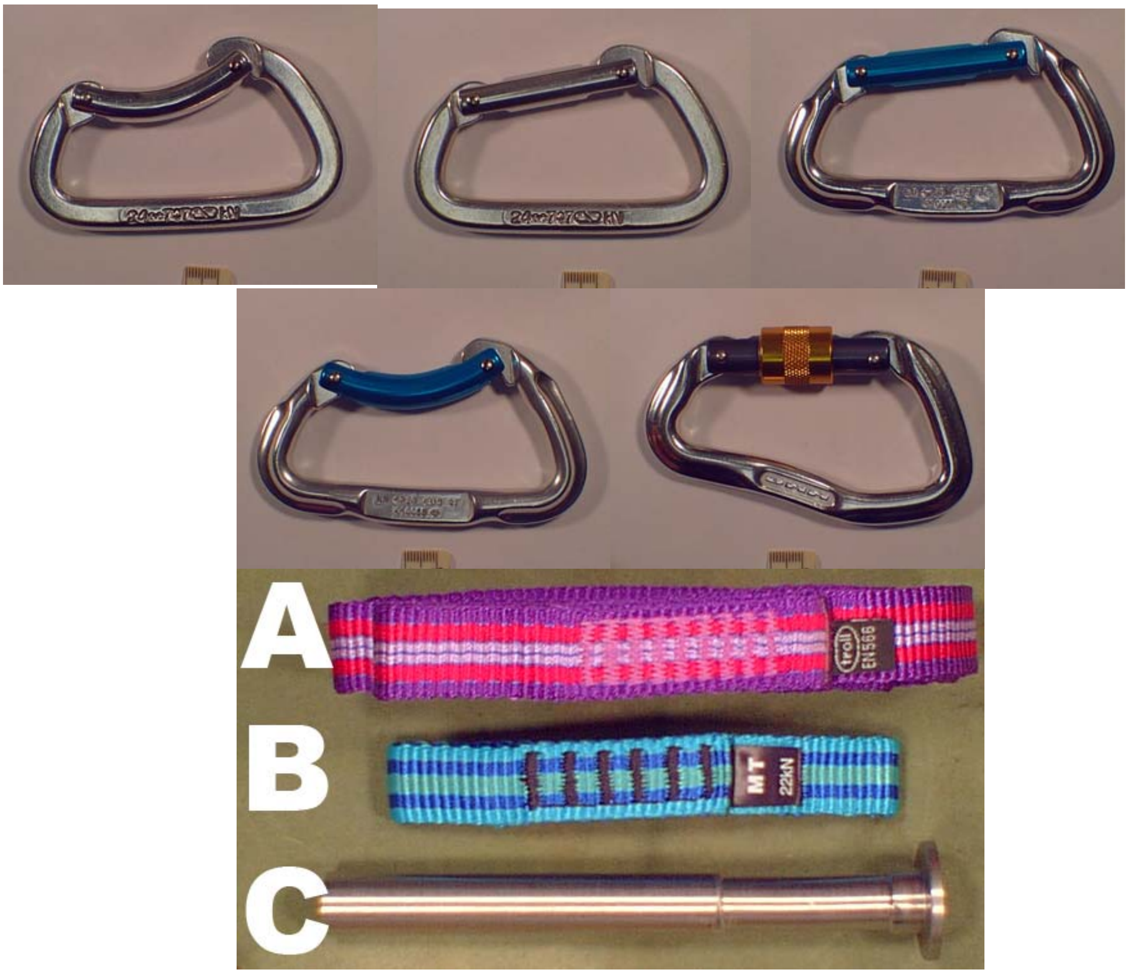

Figure 2

KB1 – HB Wales Standard 10mm Snap Straight Gate

Maximum Tensile Load along Major Axis	24kN
Maximum Tensile Load along Minor Axis	7kN
Maximum Tensile Load Open Gate	7kN

Cost £4.50

KB2 – HB Wales Standard 10mm Snap Bent Gate

Maximum Tensile Load along Major Axis	24kN
Maximum Tensile Load along Minor Axis	7kN
Maximum Tensile Load Open Gate	7kN

Cost £4.50

KB3 – Mountain Technology 10mm Snap Straight Gate MT151

Maximum Tensile Load along Major Axis	28kN
Maximum Tensile Load along Minor Axis	7kN
Maximum Tensile Load Open Gate	9kN

Cost £5

KB4 – Mountain Technology 10mm Snap Bent Gate MT153

Maximum Tensile Load along Major Axis	28kN
Maximum Tensile Load along Minor Axis	7kN
Maximum Tensile Load Open Gate	9kN

Cost £5

KB5 – DMM Tru Screw Locking Straight Gate A182

Maximum Tensile Load along Major Axis	25kN
Maximum Tensile Load along Minor Axis	7kN
Maximum Tensile Load Open Gate	9kN

Cost £7.50

Mounting Hardware

Troll – Troll 20mm wide x 60cm Long Flat Sling (**A**)

MT – Mountain Technology 20mm Wide x 26cm Long Flat Sling MT156 (**B**)

Bar – 12mm Diameter machined steel bars (**C**)

(For CAD See Appendix 2 "D:\12mm Bar Test\12mm Bar Spec")

Testing Equipment

Zwik REL 20G1 Tensile Test Machine with Rubicon Control Interface

Unlike other tensile test machines this has a crosshead which is locked into place and the load is achieved using a hydraulic piston pulling downwards. When "crosshead speed" is referred to it is describing the rate of decent of the Piston.

It is also different in that it does not use strain gauges to measure the displacement. The displacement is instead measured by the displacement of the piston as it lowers. For the purposes of this paper the displacement will be referred to as the Absolute (ABS) Stroke of the system.

Safety Equipment

Polycarbonate Plastic Screen

Rectangular section of Cotton Fabric

2.2 Experiment 1

Aim

- To test the Karabiners under closed gate conditions with realistic equipment.

Procedure

1. The crosshead was locked to the appropriate height and the tensile test machine and computer were prepared.
2. As the maximum load was predicted to be >28kN the Troll slings were folder over on them selves twice.
3. The first test karabiner was placed between the slings and any slack removed.
4. The karabiner was then wrapped in a piece of cotton cloth to catch any fragments of the specimen post-failure.
5. A polycarbonate screen was then placed between the operators and the karabiner in case of flying debris post-failure.
6. The process was then started with a constant crosshead speed of 25mm/min until the karabiner had totally failed.
7. The results were recorded onto floppy disc.
8. The fragments of karabiner were then collected and placed in sample bags for further analysis.
9. Steps 3. to 8. were then repeated a further 4 times until all of the karabiners had been tested.

Results

The data obtained from the tensile tests is plotted below in Figure 3. Table 1 compares the actual maximum loads carried by the karabiners and what they are rated to.

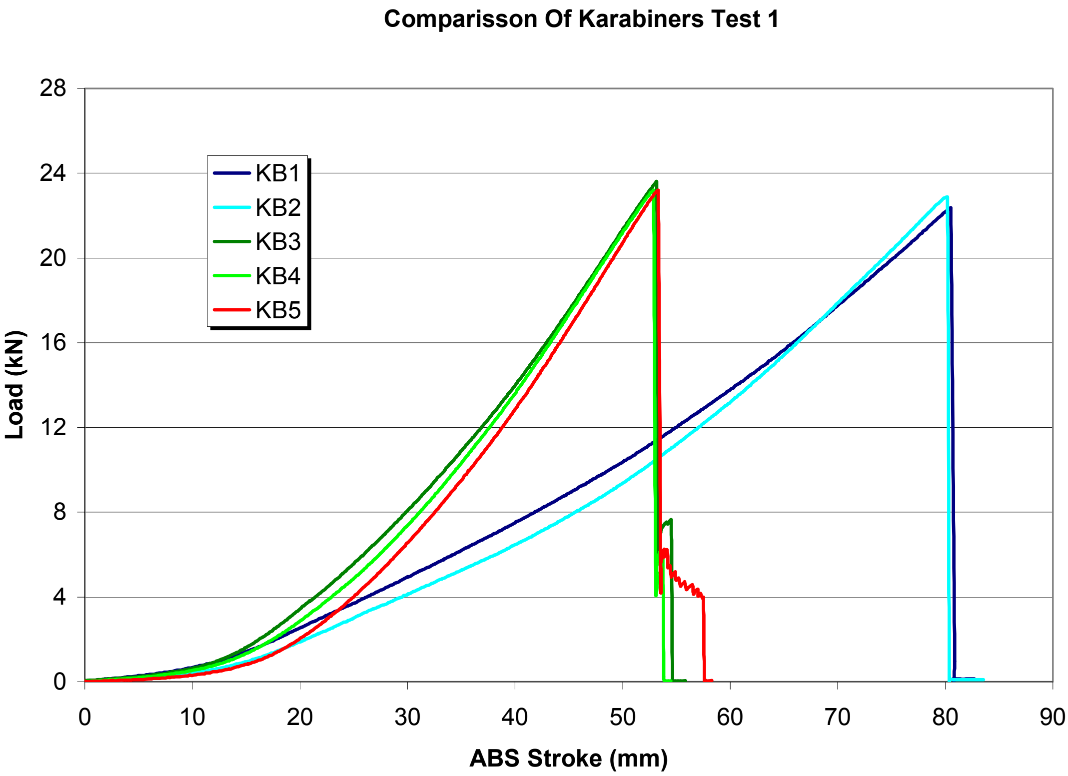

Figure 3

Karabiner	Rated UTS (kN)	Actual UTS (kN)
KB1	24	22.38
KB2	24	22.87
KB3	28	23.59
KB4	28	23.19
KB5	25	23.20

Table 1

The standard mode of failure in the closed gate test was an initial break of the hook securing the stainless steel rivet followed by the fracture of the body at the base of the long arm of the 'D' and can be seen in figure 4:

Figure 4

Te reason for the greater ABS Strokes for KB1 and KB2 is because initially one of the Troll Slings was only folder over once. This however was not strong enough and some fibre breakage occurred. For testing the higher rated karabiners to fold over both slings twice. This caused a shortening of the overall system and hence a decrease of the ABS Stroke on the subsequent testing.

2.3 Experiment 2

Aims

- To test the karabiners in open gate conditions with realistic equipment.

Procedure

1. Tape was used to cover the hooks to keep the karabiners in an open gate .
2. The crosshead was locked to the appropriate height and the tensile test machine and computer were prepared.
3. As the maximum load was predicted to be >9kN but less than 22kN the MT slings were used.
4. The first test karabiner was placed between the slings and any slack removed.
5. The karabiner was then wrapped in a piece of cotton cloth to catch any fragments of the specimen post-failure.
6. A polycarbonate screen was then placed between the operators and the karabiner in case of flying debris post-failure.
7. The process was then started with a constant crosshead speed of 25mm/min until the karabiner had totally failed.
8. The results were recorded onto floppy disc.
9. The fragments of karabiner were then collected and placed in sample bags for further analysis.
10. Steps 4. to 9. were then repeated a further 4 times until all of the karabiners had been tested.

Results

The data obtained from the tensile tests is plotted below in Figure 5. Table 2 compares the actual maximum loads carried by the karabiners and what they are rated to.

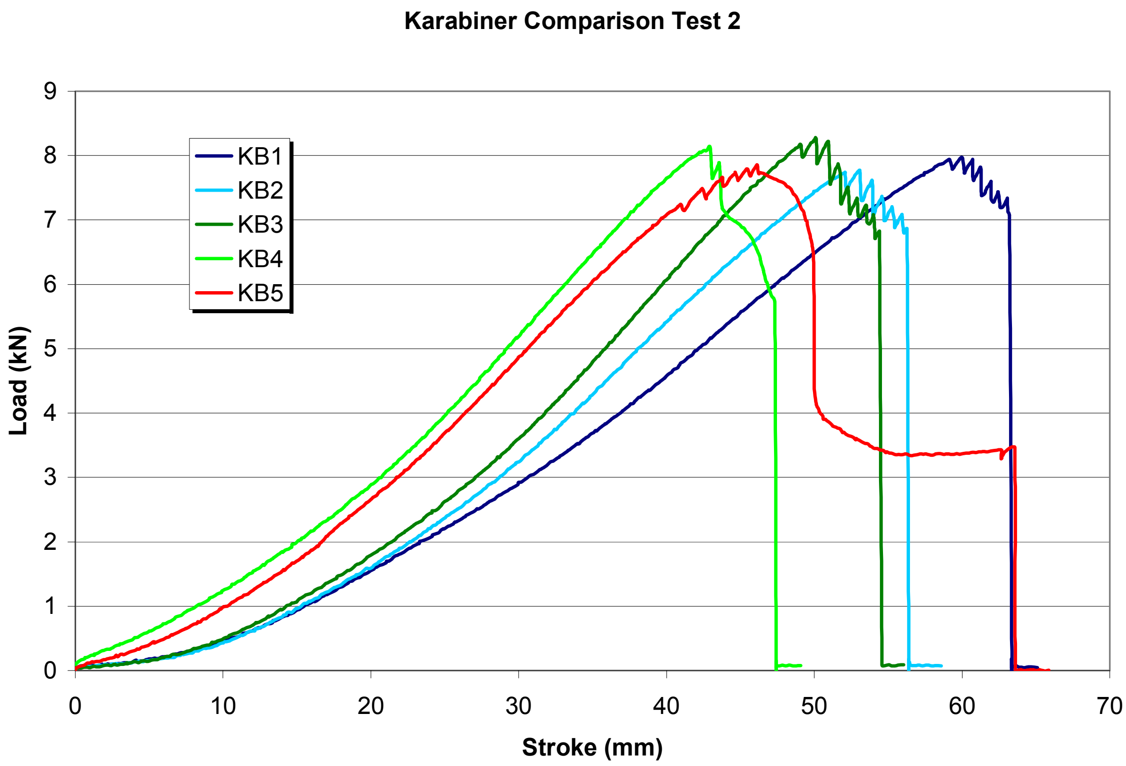

Figure 5

Karabiner	Rated UTS (kN)	Actual UTS (kN)
KB1	7	7.97
KB2	7	7.77
KB3	9	8.27
KB4	9	8.13
KB5	9	7.85

Table 2

The standard mode of failure for the open gate tests was a comparatively large deformation (compared to the closed gate tests) followed by fracture at the base of the short arm of the 'D' and can be seen in Figure 6:

Figure 6

The failure was brittle fracture characterised by little deformation and sharp edges to the cracks. As the fracture surfaces were so similar to those seen in the first test no photos were taken.

2.4 Experiment 3

Aim

- To test the Mountain Technology karabiners (which failed well below their rated load in previous tests) under British Standard test conditions.

Procedure

1. The crosshead was locked to the appropriate height and the tensile test machine and computer were prepared.
2. As this was to be a British Standard test the 12mm diameter bars were used.
3. Tape was then used to cover the hooks of one Straight Gate and one Bent Gate karabiner too keep them in an open gate state.
4. The first test karabiner was placed between the slings.
5. The karabiner was then wrapped in a piece of cotton cloth to catch any fragments of the specimen post-failure.
6. A polycarbonate screen was then placed between the operators and the karabiner in case of flying debris post-failure.
7. The process was then started with a constant crosshead speed of 35mm/min until the karabiner had totally failed.
8. The results were recorded onto floppy disc.
9. The fragments of karabiner were then collected and placed in sample bags for further analysis.
10. Steps 4. to 9. were then repeated a further 3 times until all of the karabiners had been tested.

Results

The data obtained from the tensile tests is plotted below in Figure 7. Table 3 compares the actual maximum loads carried by the karabiners and what they are rated to.

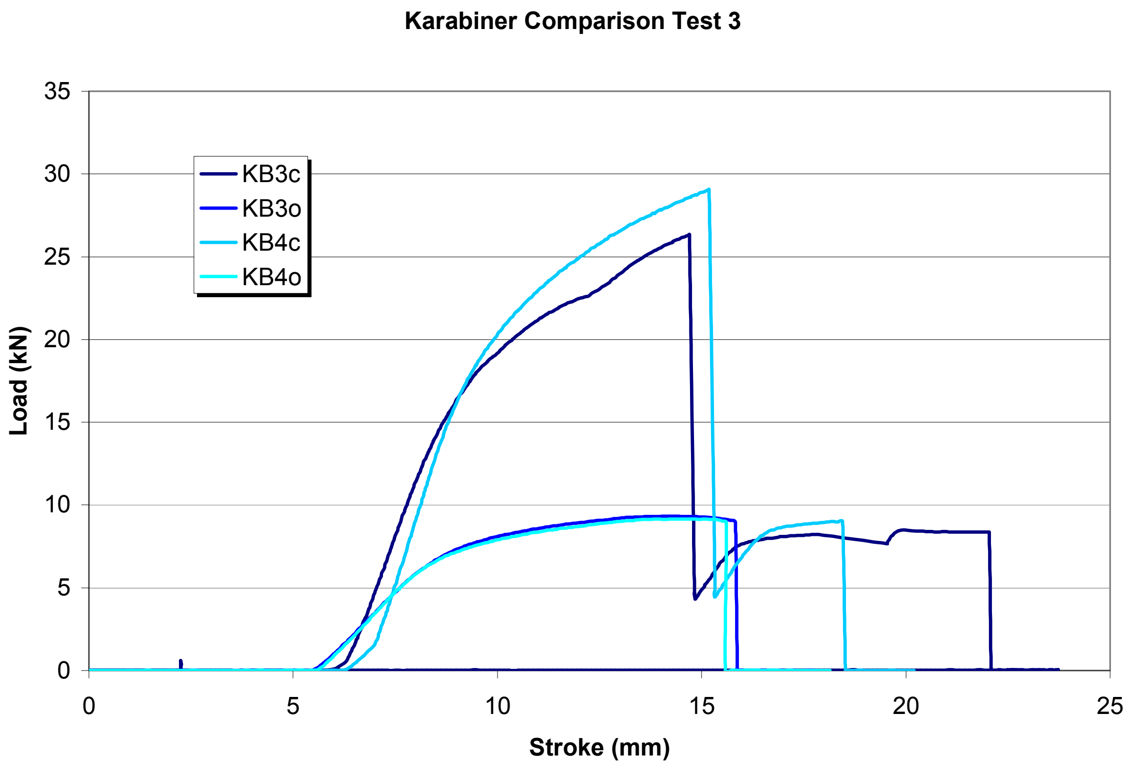

Figure 7

Karabiner	Rated UTS (kN)	Actual UTS (kN)	Elongation To Failure (mm)
KB3c	28	26.4	18.1
KB3o	9	9.32	11.4
KB4c	28	29.1	11.0
KB4o	9	9.16	13.2

Table 3

The modes of failure were similar in the British Standard test as the previous 2 tests. Closed gate tests failed at the hook first and then the base of the long arm of the 'D' and the open gate tests failed at the base of the short arm of the 'D' this can be seen in Figure 8:

Figure 8

The notable difference in this test – other than the improved maximum loads – was the increased brittlety of the fractures. The fracture surfaces were noticeably more jagged and it appeared as though less outward bending had occurred.

3. Finite Element Analysis

3.1 Basic Model Finite Element Analysis

Modelling

A section of approximately 5mm by 10mm was sketched and swept along a path approximating that of a karabiner. The reason for the width being sketched to 5mm when most karabiners are about 10mm wide was that the karabiner is be ½ symmetric about its centre.

To apply the loads to the karabiner, two 12mm diameter round bars were extruded, again in a way that symmetry could be applied.

Analysis

At this stage the main aim of the analysis was to confirm that the areas of maximum stress in finite element analysis would correlate with the points of failure observed in testing.

With this in mind the materials properties were set to generic aluminium for the body of the karabiner and structural steel for the loading bars.

Figure 9 shows the results of the initial basic analysis:

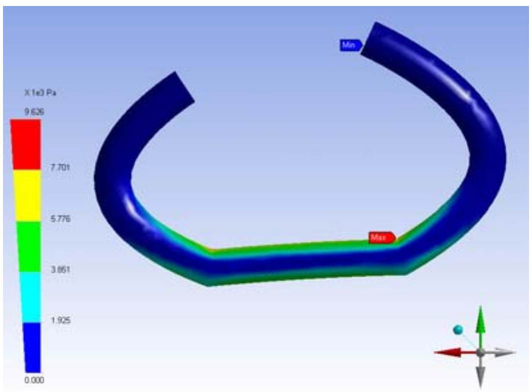

Figure 9

Discussion

The red arrow on Figure 9 shows the area of maximum stress at the base of the long arm of the 'D', another stress concentration can be seen at the base of the short arm of the 'D'.

These areas of maximum stress correspond to the areas of failure form the tests. This proves that finite elements methods are suitable for analysing karabiners, though the model is lacking realism in several key areas.

3.2 Detailed Finite Element Model

While the above model showed that the finite element method was able to highlight areas of maximum stress at the same locations as the failure points, it does not accurately represent any of the karabiners tested. In this section it was attempted to create amore accurate representation of KB3 – Mountain Technology 10mm Snap Straight Gate and the test conditions of Experiment 3.

Modelling

A model was constructed using more advanced techniques than above and used measurements taken from KB3. The model Created can be seen in Figure 10. Again the Karabiner was created with ½ symmetry about its centre.

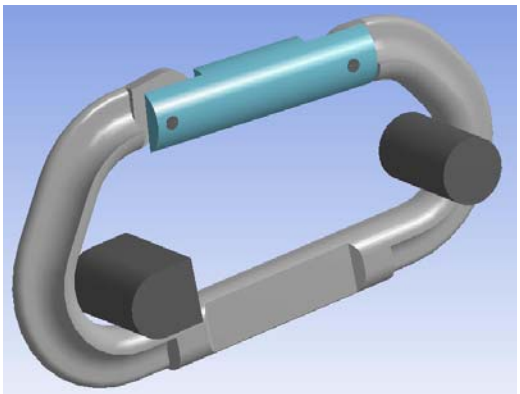

Figure 10

Material Properties

For this analysis 3 materials were required to be input for various components.

The Body and Gate are made from 7075 T6 Heat Treated Aluminium.

The Pins are made from Tempered 440A Stainless Steel.

The Bars are made from generic Structural Steel.

Property / **Material**	**7075 T6 Alu**	**440A Tempered SS**	**Structural Steel**
Young's Modulus (GPa)	71	200	200
Density (kg/m^3)	2800	7800	7850
Poisson's Ratio	0.33	0.3	0.3
Yield Strength (MPa)	505	1650	250
UTS (MPa)	572	1790	460

All Materials Data taken from Appendices of **[3]**.

Analysis

The model was then solved as a Static Structural Linear Elastic problem with the ANSYS Multi Physics Solver. Results for both Total Deformation and Equivalent Von-Mises Stress calculated and plotted.

For a sample Load of 1500N plots can be seen for Stress in Figure 11 and Deformation in Figure 12:

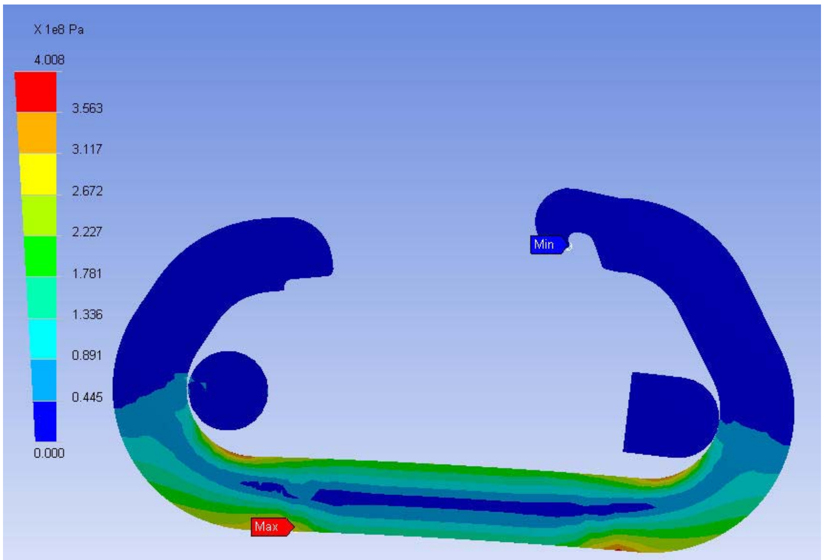

Figure 11

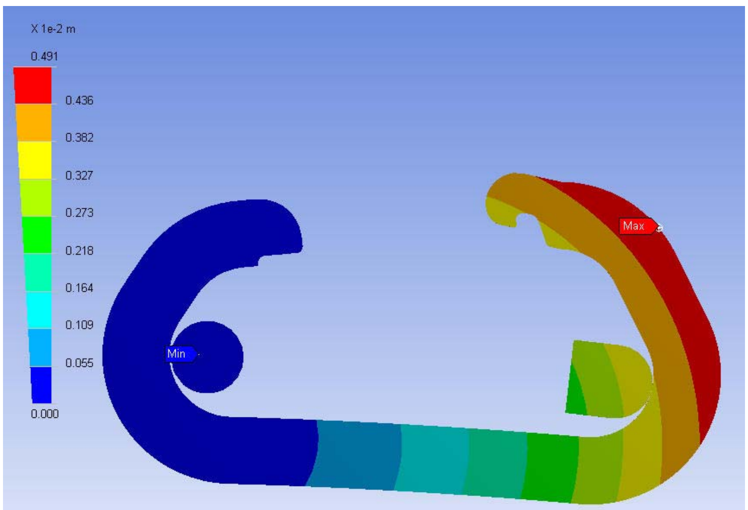

Figure 12

4. Discussion

4.1 Experiment Discussion

It is interesting that that the majority of the karabiners failed well below their rating when loaded with climbing equipment. In the first two tests the Mountain Technology karabiners failed, on average, at a load 12.5% less than their rated maximum load. However this improved to failing on average 1% higher than their maximum rated load when the British Standard Test was used.

While in closed gate situations, the difference between a karabiner failing at 23kN and 28kN is academic - as a fall of 12kN will kill you - the difference in an open gate situation is much more serious. Ropes, harnesses and most other climbing equipment is rated to 12kN and while karabiners, when properly used, are rated to a much higher load, there is always the danger of improper use or bad luck. In these cases the difference between an open gate failure at 7.8kN and at 9kN is literally life and death.

While the British and European Standards only require an open gate strength of 7kN it would be prudent to increase this as much as is practicably possible incase of improper use bad luck or loading not precisely along the major axis with 12mm diameter steel bars.

The advantage of the British Standard test is clear, it provides a reliable way test karabiners in an easily reproducible manner. It is also beneficial for academic research as it is considerably easier to create a computer model of the simple case of the British Standard test, rather than the exceptionally complex loading created by climbing equipment.

4.2 Finite Element Analysis Discussion

Two main things hampered the effective use of finite element analysis in this project. The first was the difficulty of modelling the incredibly complex shapes of karabiners and the second was the lack of detailed material properties for the aluminium used to make the karabiners.

The second option for improving modelling would be to use a 3D scanner and import the geometry. This would result in a very accurate model of the karabiner which would yield accurate results when analysed.

The final option for overcoming the problem of complex geometry is to either design your own karabiner and have it made to your specifications or to obtain the manufacturers original cad drawings. Reverse engineering the geometry from the product is always problematic, however if you start with a clean slate and create your own models or if you have access to the source models, things are simplified immensely.

For the purposes of this report all karabiners were assumed to be made from 7075 T6 Heat Treated Aluminium, this is an acceptable assumption as it is the most likely material and other alloys have similar properties. This however, is not the best situation, unfortunately manufacturers don't tend to disclose the precise alloys or treatments their products undergo for competition reasons.

4.3 Future Work

4.3.1 Future Experimental Work

- A more detailed study of the characteristics of a single karabiner under different loading situations:
    - Different Loading Apparatus; Ropes, Wires, other Karabiners etc.
    - Dynamic Loading; Attempt to recreate a fall.
- Investigate the differences in performance of Screw Gate karabiners.
- Investigate the failure modes of Wire Gate karabiners.
- Determine the materials properties for a karabiner by creating specimens to test and carry out metallographic analysis on large displacement tests.
- Use a high speed camera to view the karabiner failing.

4.3.2 Future FEA Work

- Create a scanned 3D Model for greater accuracy.
- Attempt to create a more realistic geometry model.
- Attempt to model a screw gate karabiner.
- Model the Gate and Pins separately and determine loads appropriate for this detail.
- Investigation and validation of loading methods.
- Optimization of; Shape, Profile and Topography.

4.3.3 Future Design Work

- Use information from the above research to create an optimized karabiner in terms of both geometry and materials used.
- Investigate the possibility of using composites, ceramics or polymers in a karabiner design.
- Construct a prototype of a design and test it.
- Investigate locking mechanisms and attempt to improve on them.

5. Conclusions

In conclusion the strength of climbing karabiners is dependant on many variables. These include but are not limited to; the way they are loaded, the material used in construction, shape, gate closure and quality of manufacture.

In this project the variable which had the greatest effect on the failure strength of karabiners was not the cost, the complexity of their design or the type of gate but simply the loading. This is a valuable result to have reached because it highlights that even the most elaborate of climbing equipment must be used properly or its effectiveness is seriously diminished.

This project has also highlighted many directions that future research could go in. From gaining better empirical knowledge of karabiners through testing, to improving computer models, to using all facets of knowledge to improve or evolve current designs.

Finally it is important to conduct research on all climbing equipment to make sure that standards and the testing for those standards is homogenous to ensure that it serves the safety and best interests of the end users.

6. Acknowledgements

I would like to thank; Dr Andrew McLaren, my project supervisor, for help, support and encouragement throughout the whole project. Mr Andy Crockett, Manager of the Materials Testing Laboratory, for invaluable help performing the tensile tests in the experimental phase of my project. Mr James Kelly, Technician, for photographing the results of my tests and for performing metallographic analysis on a specimen. Mr Chris Cameron, Lab Superintendent, for machining the "12mm Steel Bars" used in the British Standard tests.

I would also like to thank; Mr Peter Macdonald, President of the Scottish Mountaineering Club, for input on his experiences with karabiners. Mr George Adam, a family friend who is also an accomplished climber, mountaineer and all-round-outdoorsman, for some very frank input on the real-world use of karabiners.

7. References

1. Materials In Sports Equipment; Chapter 11 Materials In Mountaineering

Chapter By: Dr J.R. Blackford, Book Edited By: Mike Jenkins

ISBN 1 85573 599 7, Woodhead Publishing Ltd.

2. http://bsonline.techindex.co.uk/

Standard Number EN12275:1998

3. Material Science And Engineering: An Introduction, 5th Edition,

William D. Callister, Jr.,

ISBN 0-471-32013-7, John Wiley And Sons, Inc.

http://www.hbwales.com/

Information on KB1 and KB2. (At time of printing site is being remodelled)

http://www.mountaintechnology.co.uk/

Information on KB3 and KB4.

http://www.dmmclimbing.com/

Information on KB5. (At time of printing model discontinued)

http://www.petzl.com/ (Sport Section)

Information on proper use of Karabiners and safety inspection.