Failure Modes of Climbing Karabiners: Technical Paper

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Abstract

This paper investigates the failure modes of karabiners and examines if the British standard for karabiner testing is representative of real world use of karabiners. Initially statistical testing was carried out under simulated climbing conditions on a basic straight gate and bent gate karabiner. It was found that the karabiners did not all fail in the same way and there was a variation between karabiners of the same type. The tests were repeated for a further karabiner of each type however this time the karabiners had five strain gauges attached. This showed how the strain or deformation in the various parts of the karabiner built up as it was loaded. This led to a number of interesting results showing that the strains in different parts of the karabiner were different for a bent and straight gate. Both karabiners used were also subjected to a number of materials tests to determine method of manufacture and exact material properties. It was found that the karabiner is made from Aluminium 6061 and is produced by extrusion through a die followed by rolling. There is very little difference in hardness through the cross section of the karabiner. Lastly a number of dynamic tests were carried out on strain-gauged karabiners. This test simulated a real world fall of an average weight climber. This series of tests brought to light a number of interesting results, which help better understand how karabiners fail and that real world falls are very different from laboratory test conditions. The test showed that various parts of the karabiner are subject to far greater strains under dynamic loading than in the quasi-static case.

Nomenclature

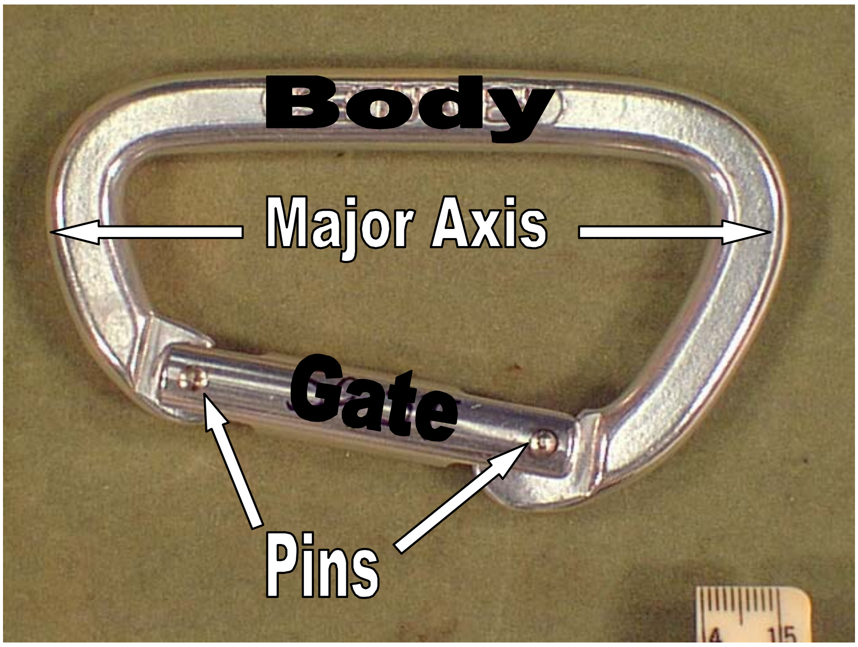

Figure 1: Karabiner Main Features

BG	HB Wales 10mm Clipper Bent Gate
SG	HB Wales 10mm Clipper Straight Gate
Troll	20mm wide by 60cm long flat sling
BL	Breaking Load

All units in SI unless otherwise stated

1.Introduction

1.1 What is a Karabiner?

A karabiner is a roughly D-shaped piece of metal with a spring-loaded gate. Karabiners are used in mountain climbing to connect various pieces of equipment and to arrest the fall of a climber. As such a vital piece of safety equipment their strength is very important. They have uses in both industry and sport. This project will be looking at karabiners used in sport climbing.

1.2 Types of Karabiner

Body shape

Karabiners come in a variety of different shapes and sizes most of which are a variation of the asymmetric D-Shape. There are a number of different “exotic” variations on the simple D-shape of which some are; ovals, pear shapes and offset D-Shapes.

These various different shapes offer different properties for different climbing situations. For the purposes of this project only karabiners with the standard asymmetric D-Shape will be examined.

Body Cross Section

As with the body shape there are many variations of body cross section. The most common shape is the simple oval or circular cross section. These are simple to manufacture, strong and allow the rope to move easily across and through the karabiner.

Some other common cross sections are variations of I sections, T sections and O sections. All these have various advantages some of these being; stronger, lighter and better rope movement. These more exotic sections are harder to manufacture and therefore more costly than the basic oval. **[3]**

Karabiners often have cut outs along their lengths where there are stamped details and designs.

The karabiners, which will be studied during this project, have a basic oval cross section and they have a cut out with stamped details mid way along the spine of the karabiner.

Gate Shape

There are three main types of gates used in modern sport climbing karabiners. The first of these is the straight gate. This is a simple cylindrical rod with a vertical rectangular cut out at each end. There is a machined hole going horizontally through the gate at each end in which a steel pin goes. This pin is used to attach the gate to the karabiner body.

The second type of gate is the wire gate. This is simple piece of looped wire, which engages with a hook at one end of the karabiner body. Although wire gates look far weaker than more conventional gates they are equally as strong and considerably lighter.

The third gate type is the bent gate. This gate is the same as the straight gate but has a bend half way along its length. This makes clipping rope in to it quicker and easier.

This paper will look at karabiners with both bent gates and straight gates.

Closing Mechanism

The final part of the karabiner is the gate closing mechanism. This is the system, which holds the gate closed during normal use but allows the gate to be easily opened when necessary.

The simplest and most common type of mechanism is the snap gate. The gate has a spring assembly at its base, which holds the karabiner closed. Once the gate is open the spring mechanism will automatically close it again when the pressure is released. This is a very convenient and simple system, which is used on nearly all karabiners. It is used with all of the gate types described above. Its only flaw is that the gate can accidentally open creating a far weaker karabiner. **[3]**

The variation of the snap gate is a locking gate. Most locking gates utilize a snap gate with some kind of moveable sleeve, which prevents the gate accidentally opening. The most common type of locking mechanism is the screw gate. The gate has a threaded sleeve, which moves along the length of the gate by screwing it. When fully to the top of the gate the sleeve prevents the gate from opening.

There are a number of other locking mechanisms however they are all a variation of the moveable sleeve. These mechanisms are all specific to the company, which manufactures them. However this project will only use basic snap gates.

1.3 British and European Standards

Karabiner Standards

The British/ European standard, which governs all mountaineering connectors, karabiners included, is “BS/EN 12275, Mountaineering Equipment. Connectors, Safety Requirements and Test methods”.

This standard governs nearly all aspects of karabiner design, but, importantly it also governs the minimum tensile strengths for various loading situations and axis. It also specifies under what situation these strengths should be tested.

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

The above strengths apply for the British standard testing method. This method states that the karabiner be loaded in a standard tensile testing machine using 12mm steel bars to apply the loads. A crosshead speed of 20-50mm/min is to be used until the karabiner fails. This test is to be used for both open and closed gate situations.

These guidelines were set in 1998 and are still current.

2. Project Aims

2.1 Experimental Aims

1. To establish the failure modes of karabiners under major axis loading.
2. To compare the load at failure to the rating on the karabiner.
3. To establish if karabiners of the same type fail in the same way under similar loading.
4. To establish the variation in maximum tensile strength along the major axis over a number of karabiners.
5. To identify how the loads are distributed through the karabiner as it approaches maximum load.
6. To identify what role the gate plays in providing the strength of a karabiner.
7. To establish if the British standard test for karabiners is applicable for real world scenarios.

2.2 Materials Testing Aims

1. To identify the exact material and manufacture method of the karabiner.
2. To characterize the structure through body of the karabiner and establish if this leads to and inherent weakness.

3. Testing Apparatus

For the experiments carried out in this project a number of items of equipment were used.

3.1 Karabiners

It was decided that for this project two types of karabiner would be used. They were both of the same body type but with different gates. These can be seen in figure 3.1 and figure 3.2:

3.1.1 HB Wales Clipper straight gate

Maximum Tensile Load along major axis	24kN
Maximum Tensile Load along minor axis	7kN
Maximum Tensile Load open gate	7kN

Figure 3.1: HB Wales Clipper Straight Gate

Cost £4.50 **[4]**

For this project there were ten of these karabiners purchased. They were labelled as follows:

SG-1 … SG-8 – Statistical Quasi Static Tests

SG-ST – Strain Gauged Quasi Static Test

SG-D – Strain Gauged Dynamic Test

SG-MT – Karabiner for materials Testing

3.1.2 HB Wales Clipper 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 **[4]**

Figure 3.2: HB Wales Clipper Bent Gate

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BG-ST – Strain Gauged Quasi Static Test

BG-D – Strain Gauged Dynamic Test

BG-MT – Karabiner for materials Testing

3.2 Slings

For the attaching the karabiners to the tensile testing machine, two Troll slings were used the details of which can be seen below:

Dimensions	20mm x 60mm
Maximum Tensile Strength	22kN

4. Materials Testing

4.1 Aims

1. To determine the exact material of which the karabiners are made.
2. To determine the method of manufacture of the karabiner.
3. To determine if there is any work hardening across the cross-section.
4. To characterize the variation of structure through the karabiner and to determine if this leads to any inherent weakness.

4.2 Method

The materials testing would be done in a number of stages which are detailed below:

1. Preparation of samples taken from BG-MT and SG-MT
2. Microscopic analysis of the cross sections
3. Hardness testing of the cross sections

4.3 Preparation

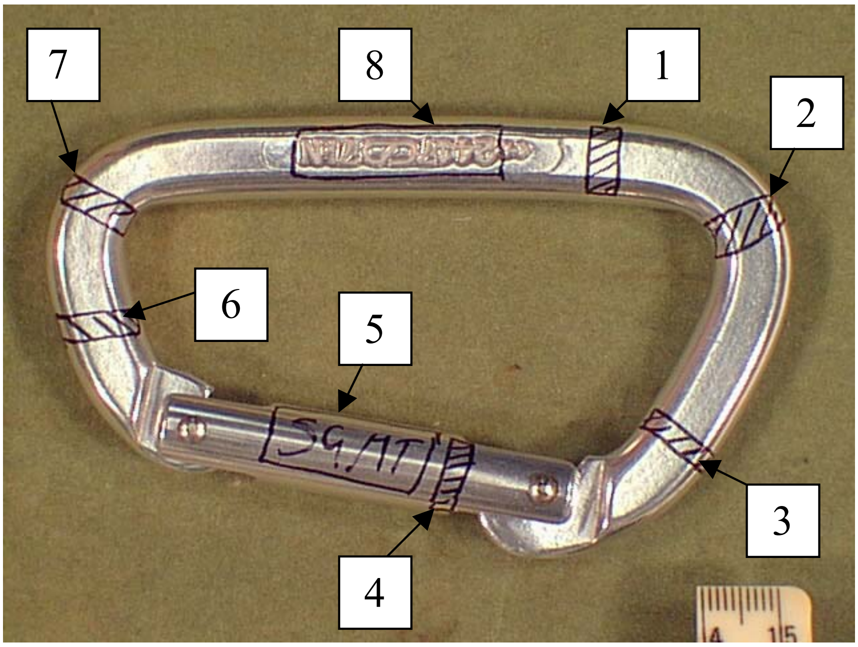

Figure 4. 1: Location of Materials Testing Samples

Before any metallographic testing could be conducted the karabiners had to be prepared. Eight samples would be taken from the karabiner. These were taken from the areas that are hatched and can be seen in Figure 4.1. Samples 8 and 5 were to be longitudinal cross-sections where as the rest were to be transverse cross sections. The number of samples and the areas from which they were taken would give a broad range of results from the areas of suspected weakness.

4.4 Procedure

1. Cutting of sections from karabiner. Sections 8 and 5 were cut with a diamond circular saw and then ground down to expose the longitudinal cross section. The remaining sections were simply cut with the circular saw.
2. The samples were polished to provide a smooth surface
3. The samples were mounted in a cold setting resin so as not to damage the structure.
4. The samples were etched using barkers etch.

4.5 Microscopic Analysis

Having prepared the samples, they could be viewed under a microscope. The acid used allowed the use of polarised light, which allowed different grain structures to be visible depending on the polarity of light used.

By cross-referencing the images obtained from each sample to those from samples of known materials, the exact material could be obtained. The material that both the SG and BG karabiners are made is likely to be Aluminium 6061. **[5]** Both the body and the gate are made of this however the pins are made of a steel alloy. Aluminium 6061 is composed of 0.6% Silicon, 1% Magnesium, 0.27% Copper and 0.2% Chrome.

From the images obtained the methods of manufacture could also be determined. The main body of the karabiner appears to have started off as a bar of Aluminium 6061 and it has been extruded through a die to give the body cross-section of the karabiner. The grain structure towards the surface of all the cross sections is much smaller than in the centre indicating the use of extrusion. There also appears to be some work hardening towards the surface. This extruded bar was then rolled in to the shape of the karabiner body. The deformation around the corners of the karabiner indicates this. The hook in to which the gate engages has been machined.

The last part of the analysis was to determine the average grain size throughout a typical transverse cross-section. To do this a series of photographs were taken across the entire width of a cross-section. The width of the cross section itself was measured and the pictures taken were taped together. The numbers of grain boundaries were counted along the width of the cross section and the width of the cross section divided by this number. This gave an average grain size of 0.0484mm

The gate appears to have started as a bar with the same cross section as the finished gate. The fact there is no deformation of the grain structure towards the surface implies that it has not undergone any process to obtain its current shape. The slots and holes have been machined in to the gate after a length of the bar has bee cut. There appears to be a slight irregularity in the machining process as the slots are slightly off centre. The BG karabiners gate was then rolled to provide the bend. The SG was left as is.

4.6 Hardness Testing of Cross Sections

Hardness testing of transverse cross-sections 2 and 7 were conducted to examine if the manufacturing produced any significant differences in hardness. This was conducted using a Vickers hardness testing machine set-up using a 5 kg mass.

The results for all of the samples showed that there was not a significant change in hardness across the cross-section. This proves that even with the rolling and the extrusion process there is no work hardening done through the body cross section of the karabiner.

The material is homogenous throughout the whole karabiner with no inherent weakness due to its manufacture or material. Having done these tests the results obtained can be used in possible future finite element modelling. The same stress strain data can be applied to all regions of the model and the exact material type is now known.

5. Quasi-Static Testing

5.1 Aims

1. To establish the failure modes of karabiners under major axis loading.
2. To compare the load at failure to the rating on the karabiner.
3. To establish if karabiners of the same type fail in the same way under similar loading.
4. To establish the variation in maximum tensile strength along the major axis over a number of karabiners.
5. To measure the macro strain in the karabiner due to slow deformation.

For this experiment karabiners BG [1..8] And SG [1..8] were to be used.

5.2 Method

1. The karabiners were marked; using a permanent pen, with a series of small crosses every 10mm around the body. The crosses were marked on using a steel rule.
2. The karabiners were photographed with the markings on them.
3. The crosshead was locked at the appropriate height and the tensile testing machine and computer were prepared for the test.
4. The troll slings were doubled over and then attached on to the karabiner and the tensile testing machine.
5. The slack in the slings was taken up by the tensile testing machine.
6. The karabiners were wrapped in a white cotton cloth and the Kevlar from the stab vest. This was to catch any flying debris from the karabiner. The cloth and the Kevlar were replaced with a polycarbonate screen for the high-speed camera tests.
7. The tensile test machine was then started using a crosshead speed of 25mm/min.
8. The results were recorded on to floppy disc.
9. The fragments were then collected and pieced back together. The distance between the crosses was re-measured.
10. The karabiners were photographed.
11. Steps 3 to 10 were repeated until all sixteen karabiners had been broken.

5.3 Results

Below are the results obtained from the tensile testing machine.

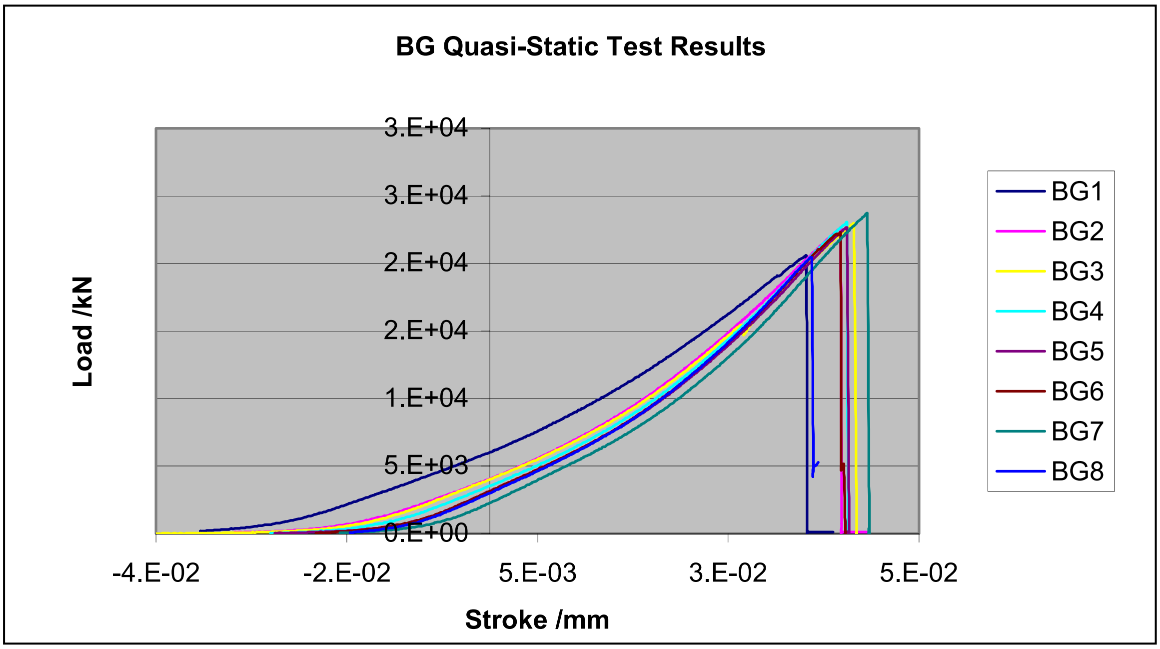

Chart 5.1: Load-Displacement Curves for a series of Quasi-Static Tests on Bent Gate Karabiners

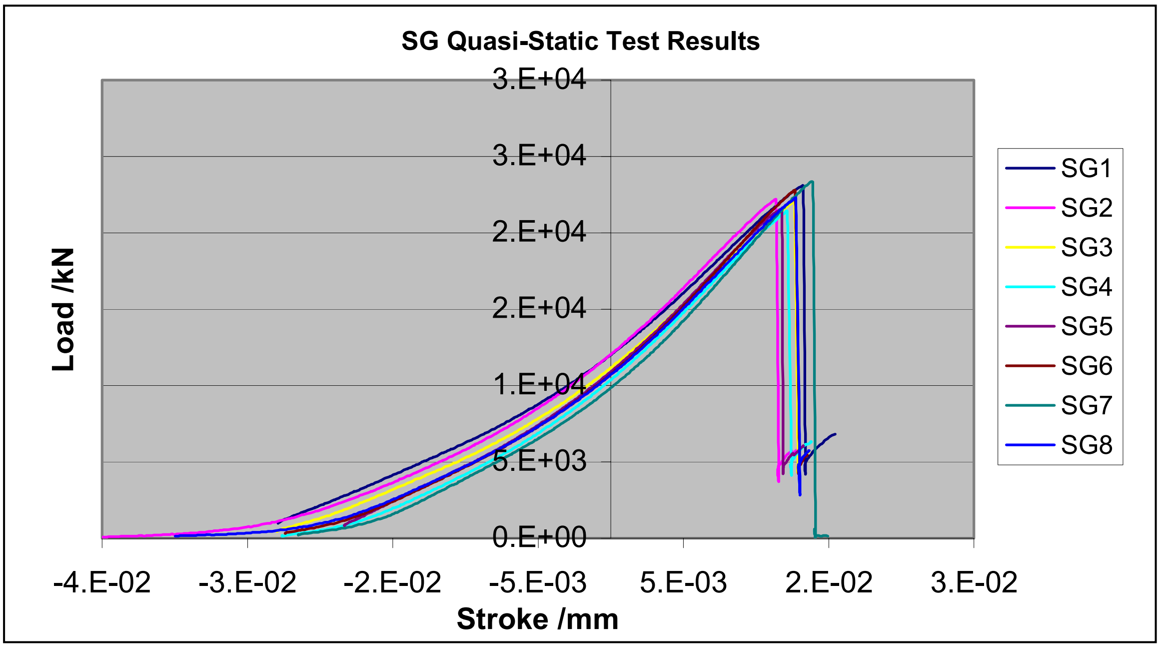

Chart 5.2: Load-Displacement Curves for a series of Quasi-Static Tests on Straight Gate Karabiners

5.4 Discussions

From the initial result it can be seen, that using the climbing slings, the karabiner will always fail below its rated breaking load. This was however proved to be correct in previous research, where in the British standard test using bars the actual breaking load was almost exactly the same as the rated breaking load. **[5]** The standard deviation in the results for the BG karabiner was found to be 1.2 kN and in the SG it was found to be 0.69 kN. For a karabiner, which is rated to 22 kN, this is a very small deviation and shows that the variation in strength between karabiners of the same type is small relative to the mean breaking load.

Initially it was thought that because there was no difference in the spacing of the crosses that there was little or no deformation. However when piecing the karabiner back together it could be seen that there was significant deformation as figure 5.4 shows.

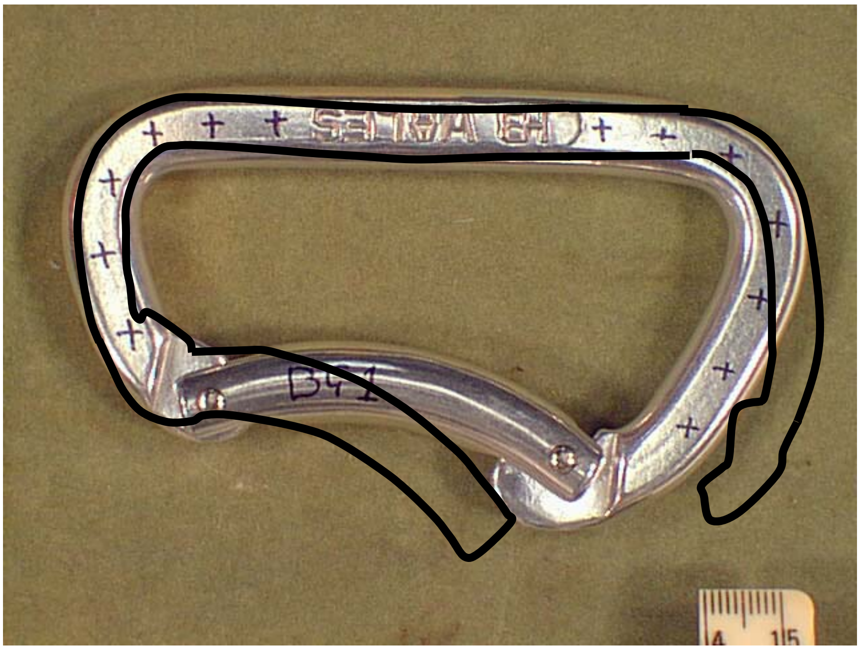

Figure 5.1: Super-Imposed Image of a failed karabiner, showing Deformation

The permanent deformation evident in the failed karabiner appears mostly around the bend, which has failed, showing that there is some ductility in the failure of the karabiner. There is also deformation in the spine of the karabiner, which can be seen to have a slight bend in it. There is no difference in the spacing of the crosses due to the fact that they are all along the neutral axis of the karabiner, and as such would not be affected by the deformation occurring around a bend. However, significant bending deformation is evident. This would be shown by measurement of displacement in the inner and outer surfaces of the bend, but this is difficult, as the slings used in the loading will tend to rub off any markings. This was addressed by measurements of displacement by strain gauge, described in section 6.

The weak points of the karabiner are all around the gate; the nose hook and the pins in the gate. The failure of the karabiner as confirmed by the high-speed camera, always starts with either the top pin of the gate or the nose hook of the karabiner failing. The karabiner then deforms around the top bend as in figure 5.3. It will then fail at either the top or the bottom bend due to small imperfections in the karabiners surface or any areas, which are damaged.

5.5 Conclusions

From the tests the failure modes of both types of karabiners have been determined. The straight gate will first fail at the nose hook, deform, then the top bend will fail. The bent gate will fail with the top pin of the gate failing and then deforming, then failing at one of the bends. There is little significant difference in the breaking loads of karabiners of the same type and little difference between the different types of karabiners.

The karabiners all fail below their rated breaking load when using slings however as suggested in other research this is not the case with the British standard test. **[1]**

Even when loaded with slings the breaking load is still far in excess of the 12 kN which dynamic climbing rope can transmit to the karabiner. This load is the maximum allowed by the British standard **[1]**. Thus even in the worst karabiner tested; the breaking load was still 8 kN greater than the 12 kN that would be transmitted.

6. Quasi-Static Testing with Strain Gauges

6.1 Aims

1. To identify how the loads are distributed through the karabiner as it approaches maximum load.
2. To provide a comparison for strain distribution up for the dynamic tests.
3. To identify the strain in the karabiner at which it will fail.

6.2 Method

1. BG D and SG D had five 120Ω strain gauges attached to them in the positions shown in the figure below and numbered accordingly. These positions were identified to be areas of maximum strain as well as areas of interest.

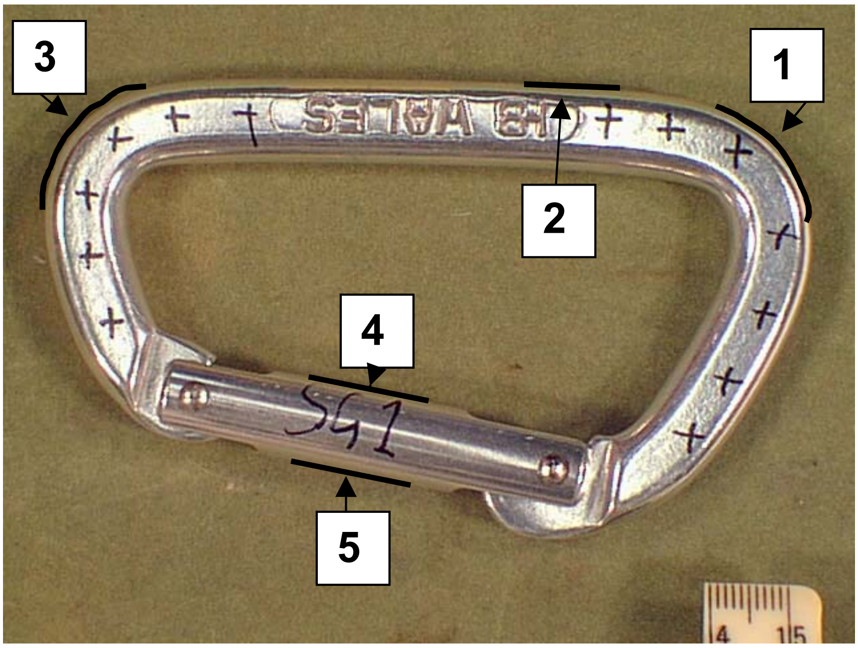

Figure 6. 1: Strain Gauge Locations and Numbers

2. The karabiners were placed in the tensile testing machine using the Troll slings to apply the loads. The slings were doubled as in the previous experiment.
3. The strain gauges were connected to the Spectra Lab interface via a wire harness.
4. The gauges were balanced and the logging process started.
5. The karabiner was wrapped in a cotton cloth and Kevlar padding.
6. The tensile testing machine was set at a crosshead speed of 25mm/min and the process started.
7. The tensile testing machine was started and load was applied until the karabiner had failed.
8. The results of both the tensile testing machine and Spectra lab were recorded to floppy disc.
9. Steps 2-8 were repeated for the second karabiner.

6.3 Results

The following are the results showing the values of micro strain against load.

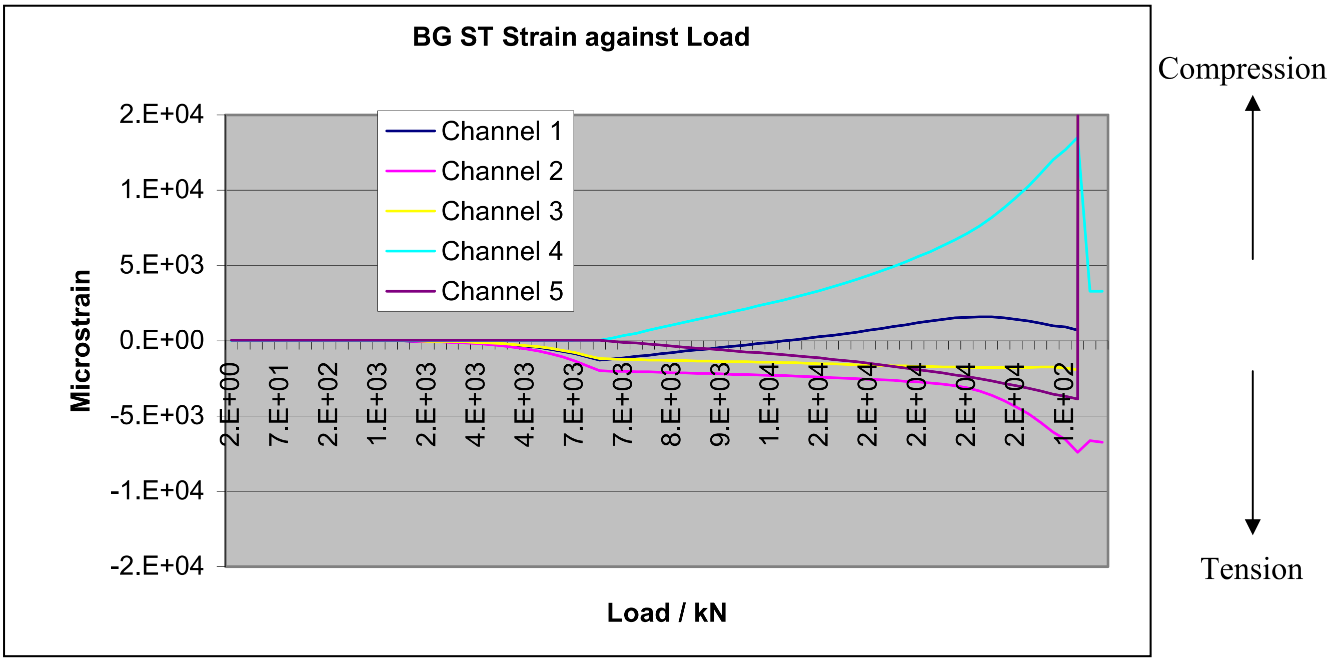

Chart 6.1: BG-ST Strain against Load Curve

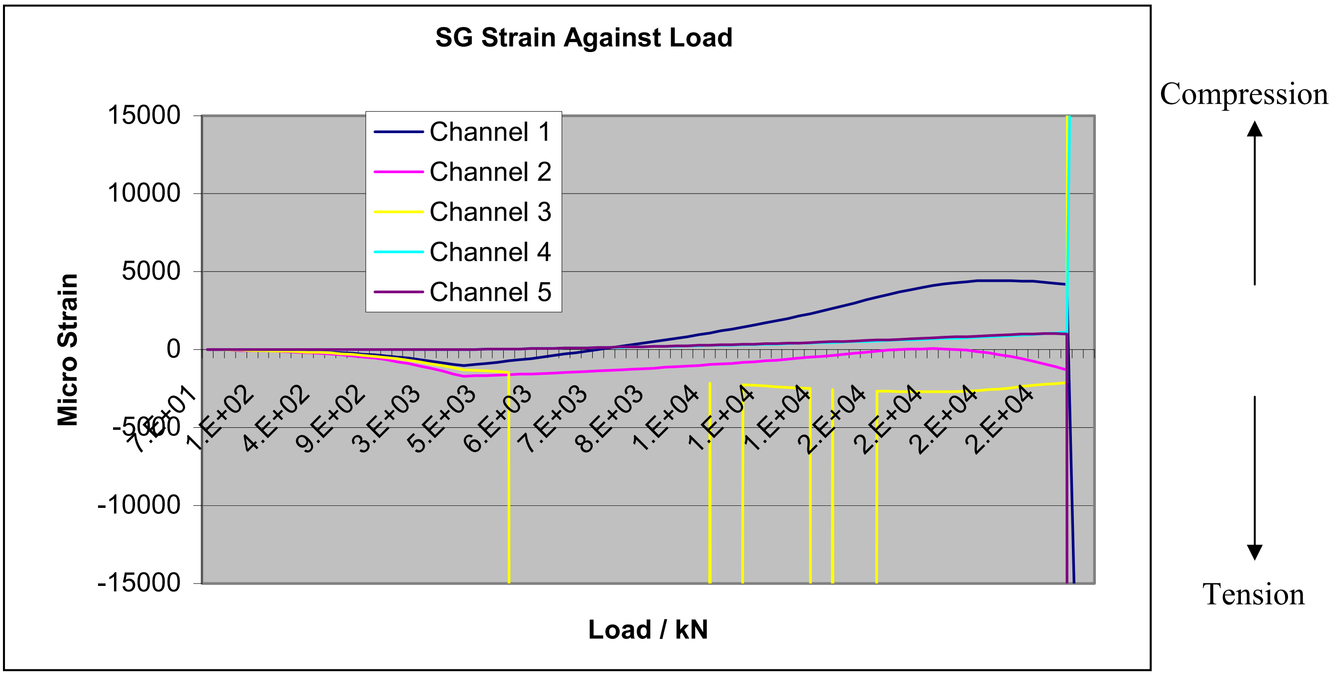

Chart 6.2: SG Strain against Load Curve

6.5 Conclusions

From this experiment there is now strain gauge data to compare any dynamic testing done. The experiment has shown how there are large strains present in the bent gate, which do not exist, in the straight gate. This explains why the bent gate always fails at the gate. The test has also shown that the bent gate karabiner has larger strains distributed throughout the whole body, than the straight gate. This is due to the straightening effect on the gate. This experiment has provided a good basis on which dynamic testing can be done.

7. Dynamic Testing

7.1 Aims

1. To establish if the strain build up to the dynamic case is the same as the quasi-static.
2. To determine if the British standard static test is a safe representation of a fall and if a dynamic test should be included.

7.2 Method

1. Four 120Ω strain gauges were attached to the karabiner, BG D, in the same places as in experiment two. The only difference was there was no channel 5, the gauge on the inside of the gate. The gates were numbered as before and the gate number was connected to the corresponding channel.
2. The karabiner was attached to the shackle of the dynamic testing rig and the rope was used to link the karabiner to the weight carrier. The length of rope used in this experiment was 1.5m.
3. A mass of 50kg was added to the weight carrier, and the carrier was raised and attached to the release mechanism.
4. The strain gauges were attached to the conditioning unit and were powered up. All the gauges were balanced and the excitement voltage set at 1V. 1V equated to 1000 micro-strain.
5. The gauges were then attached to the digital scope and the trigger was set.
6. The string on the release mechanism was pulled and the mass was dropped.

7. The data on the scope was transferred to the computer and saved.
8. Steps 3-7 were repeated for masses of 80kg and 80kg in the open gate condition.
9. Steps 1-8 were repeated for the karabiner SG D.

7.3 Results

Below are the results for the 80kg closed gate test for both SG D and BG D. The full set of results can be found in appendix A. Both the karabiners failed in the open gate condition.

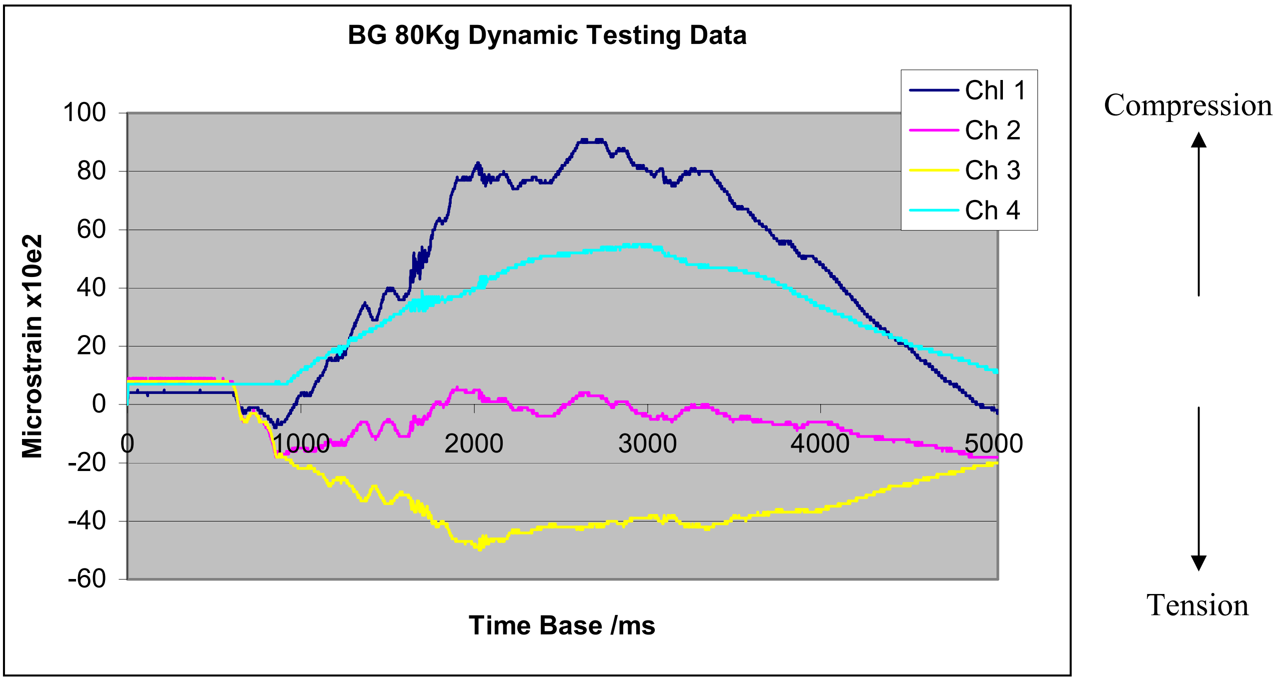

Chart 7.1: Dynamic Tests Results for BG-D at 80 kg

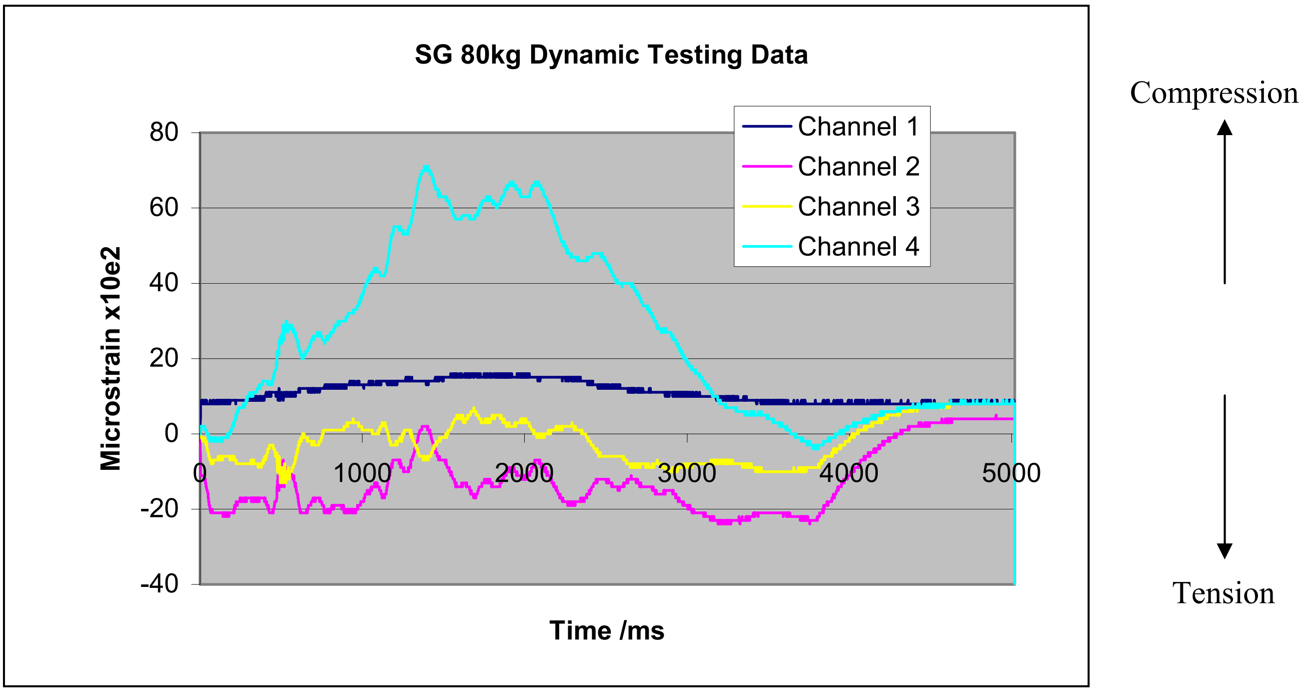

Chart 7.2: Dynamic Test Results for SG-D at 80 kg

7. 5 Conclusions

From the dynamic tests conducted it is clear to see that there are some significant differences between the quasi-static case and the dynamic case. All of the tests conducted to ensure a karabiner conforms to the British standard **[1]** are static tests whereas a real climbing fall would be more like the dynamic case. The dynamic tests show that the karabiners is strained to a considerably larger value in the gate and at the bottom bend in both karabiners. The spine of the BG karabiner is also under considerable more strain in the dynamic case.

These differences mean that the karabiner is more likely to fail in modes not covered by the British Standard **[1]**. Thus these tests show that a dynamic test conducted on karabiners would be beneficial and possibly improve climbing safety.

8. Conclusions

From the research, which has been done, there are a number of conclusions, which can be drawn. It has been established that the karabiner is probably made from aluminium 6061 alloy that is both light and strong. Due to the grain structures observed during the materials testing it is likely the karabiner was manufactured using extrusion to produce the basic cross-section and then by rolling to produce the basic shape. A machining process applied at the end has made the details of the nose hook and the gate. From the hardness testing carried out on the karabiner it could be seen that there was very little deviation in hardness through the karabiner. It appears that no significant work hardening has been done due to the manufacturing process. From the above it can be deduced that the karabiner has no inherent weaknesses due to the material or the manufacturing process. Neither of these has produced and areas from which the karabiner will fail.

The quasi-static testing has shown that all the karabiners fail at slightly different loads although the standard deviation is very small. This deviation compared to the size of the rated breaking load is insignificant. The karabiners when loaded using simulated climbing equipment rather that the bars as used in the British standard test **[1]** all fail at a breaking load that is lower than the rated value. The BG karabiners nearly all failed in the same way with the pin in the gate failing and then one of the bends failing. The SG all failed with the nose hook breaking and then the top bend failing. The failures although initially thought to be brittle factures do in fact first deform then fail, showing ductility in the failures. This ductility can only be seen by comparing a failed karabiner to a intact one as the crosses marked on the karabiner did not show this as they were close to the neutral axis.

To take the quasi-static testing a stage further, the tests were repeated for two karabiners but with strain gauges attached at different positions. This testing has brought some interesting conclusions. It shows clearly that in a BG karabiner the gate is under considerably more strain that in an SG. This is due to the gate effectively being “straightened”. Due to these larger strains in the gate there are larger strains experienced in the area of the spine of the karabiner, once again due to the gate straightening. These results also gave values of strain to compare for the dynamic testing.

The dynamic testing was used to simulate a real world climbing fall. The testing has shown that there are significant differences between the dynamic case and the quasi-static case. Both the BG and SG karabiner experience much larger strains in areas such as the top bend and the gate than in the quasi-static case. This proves that the quasi-static testing, as done in the British standard test **[1]**, is not necessarily completely accurate for all failures. For most situations it is acceptable but, for some real world falls, as shown by the dynamic testing, it would not be entirely accurate. Thus, from the research done, it can be seen that it may be necessary to include a dynamic test similar to those done on ropes **[1]**.

9. Further Research

From the conclusions drawn from the above testing there are still a number of areas which could be researched further to provide a more detailed insight in to haw karabiners fail and how to improve there design.

Experimental Work

- Further Dynamic testing using dynamic climbing rope instead of pre-stressed rope.
- Statistical dynamic testing to compare if the strains experienced are the same for the same fall.
- Dynamic testing using a number of exotic karabiners to observe how the strains are distributed for different designs.
- Further materials testing conducted on other exotic types of karabiners to see if different materials lead to any inherent weaknesses

Finite Element Work

- Produce a finite element model using the data obtained from the materials testing to further improve karabiner design.
- Detailed modelling and simulation of falls using the finite element software.

10. Acknowledgements

I would like to thank; Dr Andrew McLaren, my project advisor for his advice, help and encouragement throughout the whole project. Mr Andy Crocket, Manager of the Materials testing Laboratory, for his help during all the quasi-static tensile tests and attaching the many strain gauges to various karabiners. Mr James Kelly, Materials Technician, for performing the metallographic analysis of the karabiners, assistance with the hardness testing and the photographing of all results. Mr Eric Duncan and Chris Cameron, Lab Superintendents, for the construction and assistance during the dynamic tests and the assistance with the set-up and operation of the high-speed camera. Dr Matthew Stickland for the loan of the high-speed camera. Dr Colin Walker, for his assistance in high-speed data logging. Mr Jim Doherty, for the purchase of all testing equipment.

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