DYNAMIC TESTING OF CLIMBING KARABINERS

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ABSTRACT

This paper investigates the behaviour of two contrasting climbing karabiners under dynamic loading and examines the effects of varying loads on their overall strength. A comparison is then made against the behaviour of the two karabiner designs under static loading to establish if the British Standards test is an accurate method to rate a karabiner and if it provides a fair representation of a rock climbing fall. Experiments were carried out under different applied masses in open and closed gate loading conditions to monitor the strain distribution through the contrasting karabiners. A material analysis was carried out to gain a greater knowledge of the material properties of each karabiner. It was found that the karabiners were made from aluminium alloys which had been extruded and forged and both behaved similarly under dynamic loading, showing significant strains along the back bar of the main body. The dynamic testing displayed similar strain patterns for each karabiner, independent of the mass applied and demonstrated higher strain values in comparison to the static tests carried out. It was also found that both karabiners behaved differently under open gate conditions, producing higher strain values than in the equivalent closed gate and static test situations.

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1 NOMENCLATURE

Figure 1.1: Karabiner Main Features

Clog – Standard Clog 10mm Straight Snap Gate Karabiner

DMM – Standard DMM Spectre Wire Gate Karabiner

Gate – Indicates the strain gauge was located on the gate of the karabiner

Inner Shaft – The strain gauge was located along the middle of the inner shaft of the karabiner

Outer Shaft – The strain gauge was located along the middle of the outer shaft of the karabiner

Top Radius - The strain gauge was located around the top radius of the karabiner

Lower Radius - The strain gauge was located around the lower radius of the karabiner

O – Indicates that the karabiner was resting with the gate fixed open

C – Indicates that the karabiner was resting with the gate closed

All units in SI unless otherwise stated

2 INTRODUCTION

A karabiner is a device that serves as a climber's all-purpose connector. It is used in conjunction with dynamic climbing rope and is attached to a climbing harness to act as a safety measure to prevent a climber from a serious fall. Strength is therefore one of the key attributes which a climbing karabiner must possess. Karabiners are D-shaped pieces of metal usually made from aluminium or alloy and are designed to withstand large loads of up to 25kN. They are commonly used as safety devices in both the industrial and sporting sector. Variations in karabiner design can be found in the body shape, cross section, gate type and closing mechanism.

At present climbing karabiners are designed to tolerate large forces and are required to meet the limits set out by the British Safety Standards **[1]**. These standards are currently determined by carrying out static testing on the karabiners through the use of a tensile testing machine and steel pins are in place to support the karabiner. The British Standard ratings are as follows;

Minimum breaking load along major axis in closed gate position:	20kN
Minimum breaking load along major axis in open gate position:	7kN

Although this ensures that a karabiner can withstand a large force, this setup does not accurately simulate the applied force that a karabiner would experience in its lifetime. The main aim of this investigation is to design and build a rig which would allow for different types of karabiner to be dynamically tested in a way which would realistically represent these loads in a fall situation. Two contrasting karabiner designs, which have similar loading specifications, have been selected to compare how the difference in shape, gate fastening and weight affects the way in which the karabiner behaves.

3 PROJECT AIMS

3.1 Material Testing Aims

1. To establish the material of each karabiner type
2. To establish the manufacturing process of each karabiner type
3. To compare the structure through the body of each karabiner type
4. To establish areas of potential weakness for each karabiner type

3.2 Experimental Aims – Static Testing

1. To establish the failure modes of each karabiner type under major axis loading
2. To establish the failure modes of each karabiner type under open gate loading
3. To compare the failure loads for each karabiner against their specified ratings
4. To determine the stress distribution throughout the body of each karabiner type
5. To use the above data collected to use as a comparison for the dynamic testing

3.3 Experimental Aims – Dynamic Testing

1. To determine the stress distribution throughout the body of each karabiner type under incremental dynamic loading in a closed gate situation
2. To determine the stress distribution throughout the body of each karabiner type under incremental dynamic loading in an open gate situation
3. To discover if static testing is an adequate way to rate a karabiner and represent dynamic loading
4. To determine how the karabiner behaves under a variety of different loading values applied dynamically

4 TEST APPARATUS

4.1 Karabiners

The individual specifications have been described.

4.1.1 Clog Super 10 Snapgate

This design utilises the basic D shape with a standard symmetric cross section and forged cut out sections at each corner. The main body and gate are made from aluminium and has an overall weight of 55g.

Karabiner ratings;

Breaking load along major axis in closed gate position: 23kN

Breaking load along major axis in open gate position: 7kN

4.1.2 DMM Spectre

An aluminium alloy was used for the main body with an I-beam cross section. This design utilises a wire gate and was priced at £8. The overall weight is significantly lighter than the Clog design at 34g.

Karabiner ratings;

Breaking load along major axis in closed gate position: 23kN

Breaking load along major axis in open gate position: 7kN

4.2 Vishay Micro-measurements & SR-4 General Purpose Strain Gauges

CEA-06-240UZ-120 – Specification:

Gauge Factor	2.075±0.5%
Grid Resistance	120±0.3%
Active Gauge Length	0.006m

4.3 Slings

Two slings rated at 22kN were required to attach and hold the karabiners into position whilst completing the static testing.

4.4 Tensile Test Machine

The Zwick Tensile Test machine operates with a hydraulic piston which applies a load by descending vertically at various speeds. The crosshead speed can be altered and determines the rate of descent of the piston. The tensile test machine was used for all static tests completed.

4.5 Dynamic Test Rig

This was established by attaching an I-bolt to a suspended I-beam which would provide a stable hold for the karabiner to be kept in place. The weights could then be connected to the karabiner by a climbing rope using a figure of eight knot to maintain a realistic climbing setup. A quick release mechanism was designed to allow the weights to be held in position and be easily triggered to drop and cause an impact load on the karabiner.

4.6 Safety Equipment

1. Cotton fabric wrapped and secured around the karabiners during the static tests to contain the fragments
2. Polycarbonate plastic screen to act as a secondary measure against any possible fragments
3. Protective clothing including safety shoes and safety glasses were worn during the dynamic testing

5 PREPARATION FOR TESTING

5.1 Preparation of Karabiners for Material Analysis

- Two transverse cross sectional segments were cut using a circular saw from each karabiner and then ground down to a smooth surface; one sample from the main spine and the other from the top corner to provide a range of results
- To prevent any damage each test section was mounted in a cold setting resin to ensure that the structure maintained its original qualities.
- Every sample was etched using barkers etch and cleaned with hydrofluoric acid.

5.2 Attachment of Strain Gauges

Strain gauges were attached to each karabiner in specified positions to obtain an accurate idea of the strain distribution throughout the karabiner structure. The position of each gauge has been highlighted in Figure 5.1.

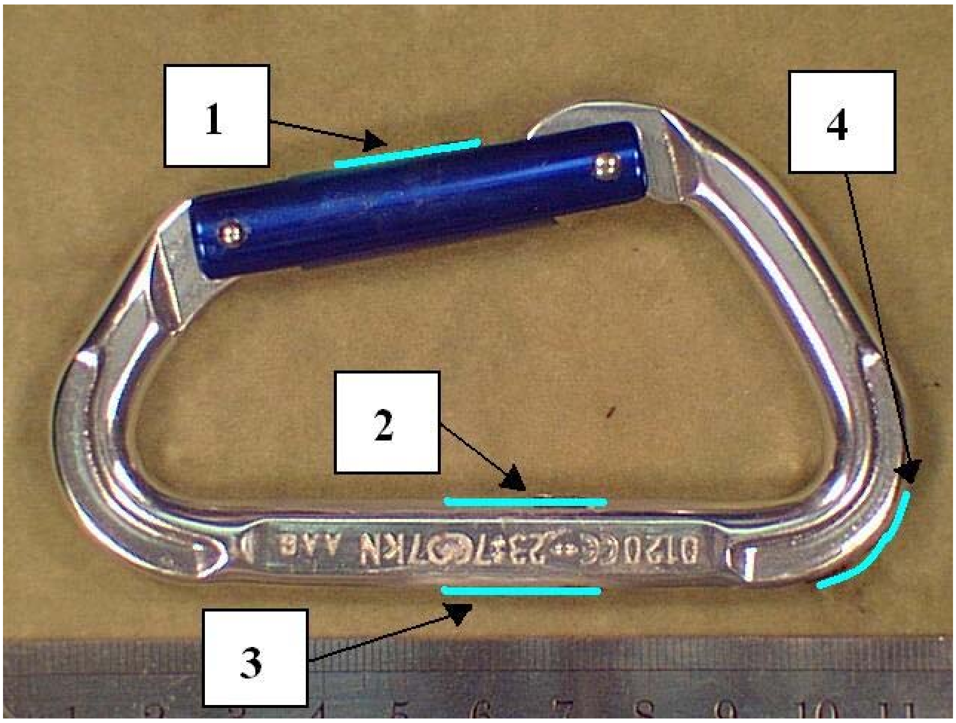

Figure 5.1: Positioning of Strain Gauges on Clog Karabiner

For the strain gauges to read accurate results it was vital that they were carefully attached to the karabiner in the appropriate manner. A routine procedure was carried out, including the preparation of the karabiner surface, strain gauge bonding and attachment of the wiring.

5.3 Setup of LabView Data Capture System

A data capture system was required to attain the readings from each of the strain gauges attached to the karabiner specimen. Due to the instantaneous response when the dynamic load was released, it was necessary to obtain as many readings per second as possible to achieve an accurate result curve from the applied load. A system was therefore setup using the LabView computer programme to measure the strain over a five second period. One thousand samples were recorded each second and the resulting list of data which was captured could then be tabulated and imported into Microsoft Excel to allow a graphical representation of the data to be formed.

6 MATERIAL ANALYSIS

6.1 Chemical Analysis

As the material of each karabiner was not stated, it was necessary to carry out a chemical analysis to gain an insight into which elements were contained within each composition. The composition data collected is shown in Tables 6.1 and 6.2.

It can be seen that both specimens contain similar elements with the exception of the inclusion of Silicon in the Clog sample. Aluminium was the primary material used in both cases, although the DMM karabiner contained a significantly smaller amount, with a percentage of only 66.05% in comparison to 85.69%. The DMM karabiner was constructed from an alloy containing higher quantities of alloying elements than that of the Clog karabiner making it better suited to a forging manufacturing process.

6.2 Microscopic Analysis

The acid used to etch the surface of each specimen allowed each sample to be viewed under the microscope with the use of polarised light. The light could be adjusted to maintain a clear image of the grain structures for each sample so that an analysis could be made. The main differences were observed in the sections cut from the back bar of each karabiner as shown in Figures 6.1 and 6.2.

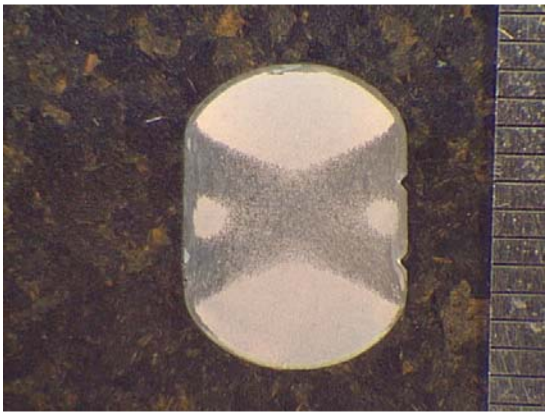

Figure 6.1: Clog Cross Section at Back Bar

Figure 6.2: DMM Cross Section at Back Bar

Both figures illustrate the difference in cross sectional area between the two designs and the alternative flow patterns produced in each karabiner. The Clog sample displayed a distinct reflective cross across the centre of the area. This shape contained elongated grains following the direction of the cross with the rest of the surface grains being much finer and uniform in comparison. There was also a different type of grain shape around the outer edge of the cross section, displaying higher regions of stress. Both areas imply that extrusion and then a forging process had been carried out on the karabiner. The karabiner would have had a circular cross section which was then deformed and resulted in higher stresses being produced in the cross formation shown.

The DMM cross section displayed slip bands along the vertical axis as a result of micro shearing due to the increased stress. These, along with precipitates, were indications that the aluminium alloy had been treated for improved hardness and toughness. It also suggested that the alloy had gone beyond its ductile capabilities; which indicated a hot forging process. The rest of the cross section had small heat grains, implying that the manufacturing process was carried out under rapid conditions reinforcing the idea that the karabiner had been hot forged.

Another noticeable difference was the method in which the strength specifications were displayed on the main body. The Clog structure used an etching type process which had a detrimental effect on the surrounding grain structure. It caused areas of raised stress as well as producing sharp edges on the surface, which were key areas for fatigue and had high potential for initiating cracks that could lead to failure.

The DMM karabiner utilised a relief method which had little effect on the grain structure. Although there were slight stress concentrations where the relief lettering met the body of the karabiner, these disfigurements to the grain size were not to the same degree as the Clog karabiner. Also, this method would pose less risk of producing fatal areas for crack propagation to initiate.

7 STATIC TESTING

Static testing was carried out in open and closed gate scenarios to identify areas of weakness and high strain and to use as a comparison for the dynamic testing data.

7.1 Procedure

- The karabiners were photographed in their original state to use as a reference for any deformation caused during the testing
- The test machine crosshead was locked at the appropriate height and the Spectra Lab programme was setup for the testing
- The slings were doubled over and looped around the karabiner to secure it in position
- The strain gauges were wired up to separate computer channels
- The slack from the slings was removed
- The karabiner was securely wrapped in cotton fabric and a polycarbonate screen was put in place for safety reasons
- The tensile test machine was started using a crosshead speed of 25mm/min and run until the karabiner failed
- The results were recorded to floppy disc
- The fragments were collected and pieced back together to view the permanent deformation
- The above steps were repeated for each karabiner type in closed and open gate conditions
- All data was imported into Microsoft Excel for further analysis

7.2 Closed Gate Results

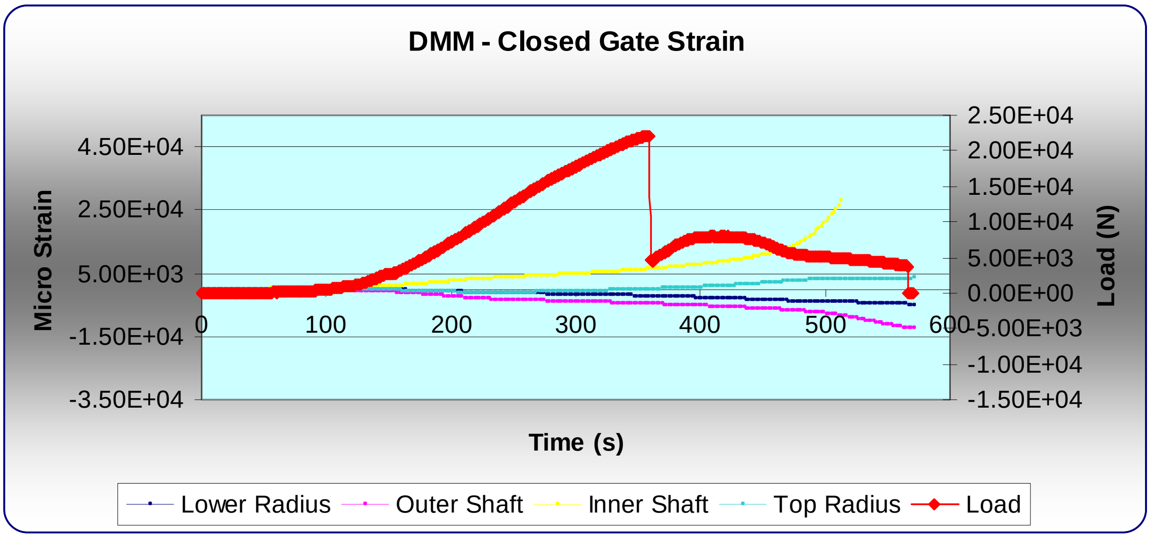

Figure 7.1: Graph Plotting Load and Strain against Time for a Closed Gate DMM Karabiner

7.3 Closed Gate Discussion

It can be concluded that both surpassed the British Standards specification of 20kN with an example of their actual failure loads and positions of failure stated in Table 7.1.

Previous experimental work has shown that the slings can have a detrimental effect on the maximum tensile load reached in comparison to steel bars during static testing. **[2]** This could be a reason for the DMM karabiner failing below its rated load.

Failure at the hook was not surprising as this section was significantly smaller in cross sectional area in both designs and would therefore result in a reduction in tensile strength in that area.

Table 7.2 shows the inner and outer shaft are key areas of strain, with the Clog design experiencing more strain in comparison to the DMM design.

After testing the DMM lower radius angle had increased and the back bar showed a distinct inwards bend which clearly demonstrates the areas of high strain and permanent deformation. It can be seen from Figure 7.1 that the karabiner experiences a significant rise in strain after the initial failure, resulting in the visible permanent deformation.

Deformation occurred at the two corners of the Clog karabiner with the top radius angle becoming tighter and the lower radius angle opening. This corresponded to the gauge data collected.

The static testing under closed gate conditions allowed the areas of weakness to be highlighted and showed that failure was most likely to occur primarily at the hook and then redistribute the load to the top radius. Both areas of failure displayed a brittle fracture, characterised by the little deformation and sharp edges to the cracks.

7.4 Open Gate Results

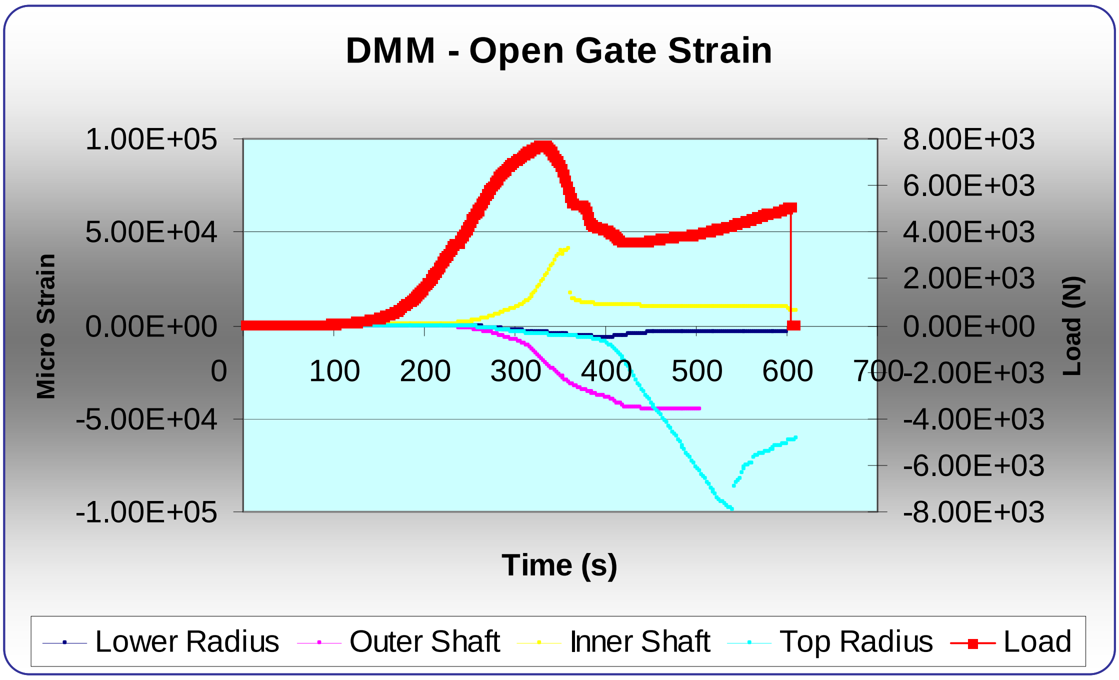

Figure 7.2: Graph Plotting Load and Strain against Time for an Open Gate DMM Karabiner

7.5 Open Gate Discussion

All karabiners passed the British Standards ratings and failed at around 7.5kN as can be viewed from Table 7.3. Similarly to the closed gate testing, the DMM karabiner failed below the company specification.

It was observed that all failures occurred along the back bar at a point close to a corner bend. The strain distribution, which can be seen in Table 7.4, showed that the strains experienced at both bends of the DMM karabiner were similar and that the back bar experienced the greatest strains during the loading.

The failed karabiners displayed a greater permanent deformation under the open gate conditions, an example can be seen in Figure 7.3. Although the shaft was the area of greatest strain at the initial failure, it can be observed that the top radius of both designs was heavily deformed during the loading. It can be concluded that after the maximum open gate loading is reached, the karabiner begins to deform significantly and the load is redistributed with the majority of the strain acting at the top corner. This corresponds to the strain distribution in Figure 7.2.

Figure 7.3: DMM deformation after Open Gate Loading

This highlights the important role that the gate provides in distributing the loading and strain throughout the karabiner structure. When the gate was made redundant, parts of the karabiner were experiencing up to six times the amount of strain under a significantly smaller maximum load.

Similarly to the closed gate static loading carried out, the open gate tests resulted in brittle fracture occurring in both the Clog and DMM karabiners as can be seen in Figure 7.4

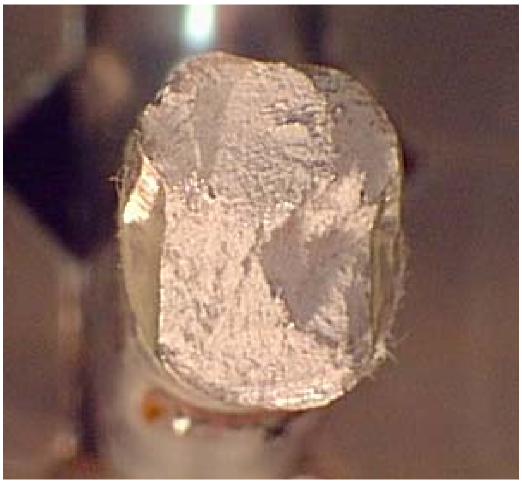

Figure 7.4: Brittle Fracture for Open DMM Karabiner

8 DYNAMIC TESTING

8.1 Procedure

The procedure used the dynamic setup described in section 4.5.

- The karabiners were photographed in their original state to use as a reference for any deformation caused during the testing
- Four 120Ω strain gauges were attached to the allocated positions on each karabiner as previously described in section 5.2
- The karabiner was attached to the I-bolt
- The crane was then used to raise the weights with a sling used to attach the weights to the quick release mechanism
- The strain gauges were connected to the corresponding channels on the data capture system
- The trigger on the programme was initiated and the string on the release mechanism was pulled to release the mass and simulate a climbing fall on the karabiner
- The data from the LabView programme was saved in the corresponding file to be imported into Microsoft Excel for further manipulation and analysis
- The above steps were repeated to gain a second set of results to e
- The above steps were repeated for different mass values, increasing in increments of 20kg from 17kg to 77kg
- The above steps were repeated for both the Clog snap gate and the DMM wire gate karabiners
- The above steps were repeated under open gate conditions with an applied mass of 27kg

8.2 Experimental Results

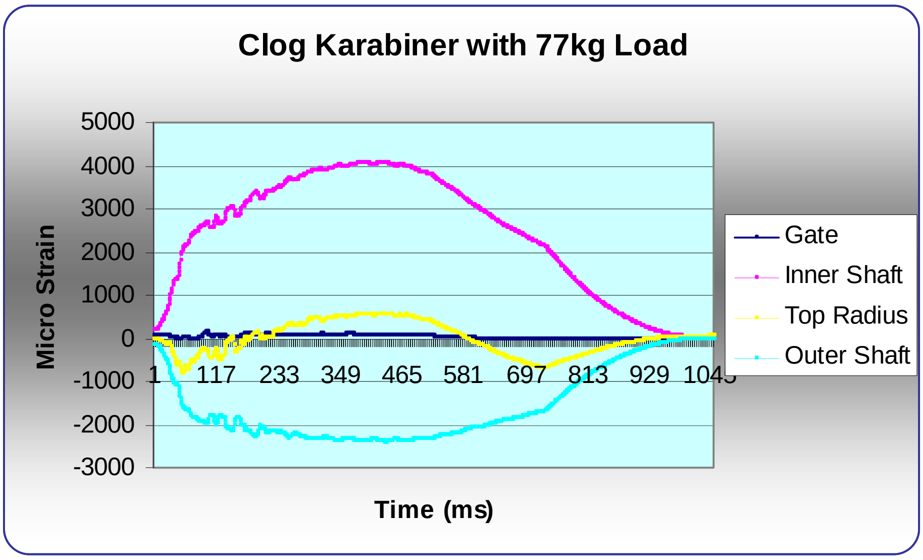

Figure 8.1: Graph plotting strain distribution through Clog karabiner at 77kg Load

Both karabiners behaved similarly under dynamic loading. The strains in Figure 8.1 show tension in the inner shaft and gate whilst compression in the outer shaft. This indicated that the back bar tended to bend inwards under dynamic loading, a similar result to the static tests.

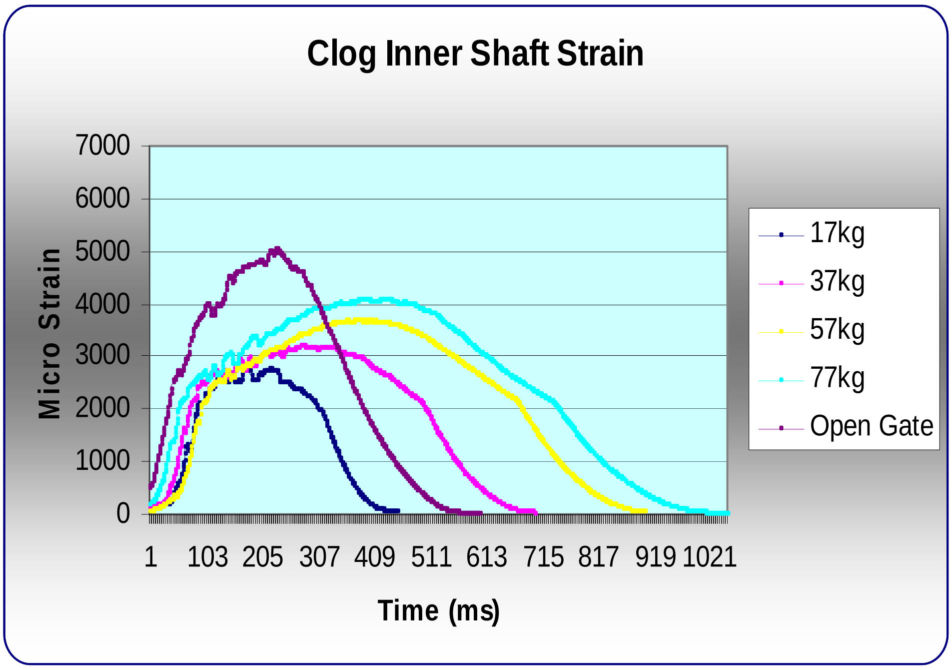

Figure 8.2: Graph plotting strain distribution along Inner Shaft of Clog karabiner for various loading values

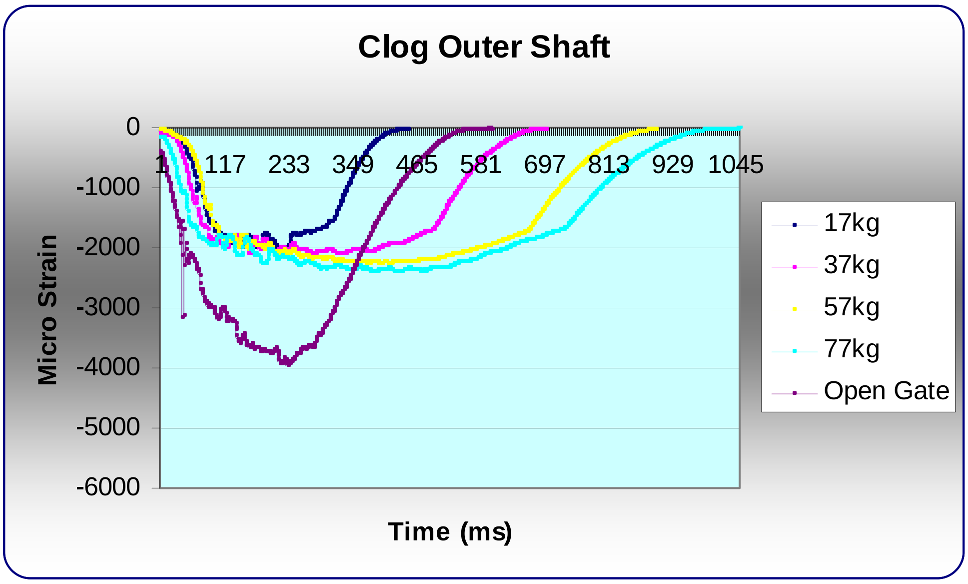

Figure 8.3: Graph plotting strain distribution along the Outer Shaft of Clog karabiner for various loading values

Figure 8.2 and 8.3 showed how the strain curve followed the same basic shape, independent of the mass applied. The maximum strains experienced at the inner shaft of both karabiners are displayed in Table 8.1 which shows how the DMM design experiences an overall greater strain for a set mass. One explanation is the significant reduction in cross sectional area and shape.

The two graphs also show the strain curves follow similar loading and unloading regardless of the mass applied. The time for each response and the maximum strain both increase due to the additional strain energy as more mass is added.

It can be viewed from Table 8.1 that the maximum strain experienced is greatly increased under open gate conditions although the time taken for the impact to occur and the energy to be absorbed and then dissipated remains around the same as would be expected for the same 27kg mass under closed gate conditions.

Table 8.2 shows a comparison between the static and dynamic testing and highlights the significant strain difference experienced under the different testing methods.

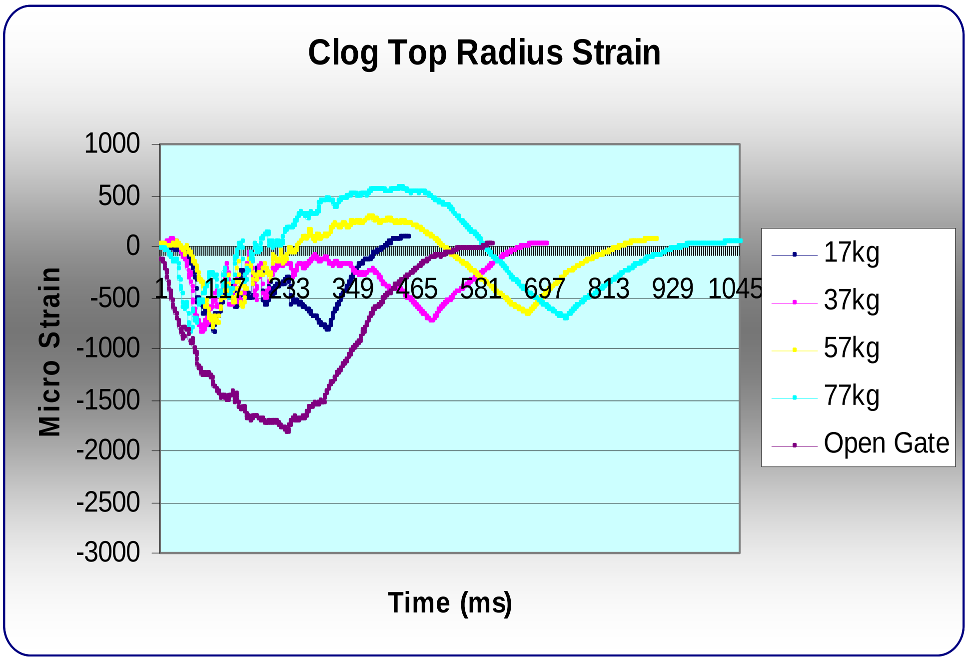

Figure 8.4: Graph plotting the strain distribution along the Top Radius of the Clog karabiner for various loading values

Figure 8.4 highlights the initial compressive strain which changed into a tensile strain for the majority of the response. The compressive strain appears to represent the loading until the gate comes into contact with the hook and then the load is redistributed and tensile loading will begin. The top radius strain distribution highlights the difference between the two designs in this area as the DMM design showed significantly less tensile strain at this point. The open gate loading displayed a purely compressive curve for both karabiners.

9 CONCLUSIONS

It was established that both karabiner types were aluminium alloys containing similar alloying elements. The DMM design contained a higher proportion of alloying elements, making it more suitable for a forging process. The Clog karabiner was manufactured through an extrusion process and then forged, whilst the DMM karabiner was hot forged. Potential weaknesses were detected due to method in which the specification ratings were displayed on the karabiner body, although none of the test specimens failed at these points.

Both karabiners displayed similar characteristics under dynamic loading, with bending occurring across the back bar and the top radius. The strain curves allowed the distribution to be visualised throughout the impact and allowed common trends and patterns to be made between both designs with varying masses.

The DMM karabiner received a greater amount of strain during the dynamic loading. One explanation for this is due to the dramatic difference in cross sectional area between the two designs. The fact that the DMM karabiner can tolerate similar loading values with this weight reduction displays the way in which it has been more efficiently designed with a larger outer edge to prevent buckling and an increased strength to weight ratio. Although a greater amount of strain is experienced through the DMM karabiner under loading, this was not a functional concern when considering the loading range likely to be endured by the karabiner in a climbing situation.

The static testing proved that both karabiners met the British Standards and that brittle fracture was evident at the areas of failure. The comparison between the static and dynamic tests showed variation in the strains experienced through the karabiner under these different testing methods. The maximum strains achieved under the dynamic conditions for an applied load were greater than those experienced during the static tests in the open and closed gate conditions which indicated that modifications could be made to the current British Standards testing to achieve a more accurate representation of the loading experienced on a climbing karabiner in a fall situation.

10 ACKNOWLEDGEMENTS

It would not have been possible to complete this Thesis without the help of the many others that have contributed to the content of this project. First, I would like to thank Dr Andrew McLaren, my project supervisor, for his encouragement and guidance throughout the duration of the project.

I would also like to thank; Mr Chris Cameron, Lab Superintendent, for the construction and assistance during the dynamic tests that were carried out, as well as assistance with the initial setup of the LabView data capture system. Mr Andy Crocket, Manager of the Materials testing Laboratory, for his assistance performing all of the static tests and for the instruction on how to attach the many strain gauges required for each experiment. Mr James Kelly, Materials Technician, for performing the metallographic analysis on both karabiner designs and for photographing all test specimens prior to, and after all testing. Mr Jim Docherty, Stores Manager, for the purchase of all the karabiners and necessary equipment for testing.

11 REFERENCES

[1] **British Safety Standards – Personal Protective Equipment for falls from a Height - Connectors**
British Standard
BS-EN 362:2004, 892:1997 2004

[2] **Failure Modes of Climbing Karabiners**
Daniel Wessel, Supervisor: Dr A McLaren
University of Strathclyde
Technical Paper, 2005

[3] **British Safety Standards – Mountaineering Equipment – Dynamic Mountaineering Ropes – Safety Requirements and Test Methods**
British Standard
BS-EN

TABLES

Table 6.1: Clog Chemical Analysis Data

Clog Karabiner					
Element	**Line**	**App. Conc**	**k ratio**	**Intensity corrn.**	**Weight%**
C	K_SERIES	0.54	0.00249	0.1589	4.58
Mg	K_SERIES	2.81	0.01928	1.1742	3.24
Al	K_SERIES	69.8	0.51418	1.1032	85.69
Si	K_SERIES	0.22	0.00181	0.4271	0.71
Zn	K_SERIES	3.6	0.03598	0.8441	5.77
Totals					100

Table 6.2: DMM Chemical Analysis Data

DMM Karabiner					
Element	**Line**	**App. Conc**	**k ratio**	**Intensity corrn.**	**Weight%**
C	K_SERIES	2.41	0.01113	0.2032	28.17
Mg	K_SERIES	0.76	0.0052	1.1163	1.62
Al	K_SERIES	30.39	0.22383	1.0935	66.05
Zn	K_SERIES	1.42	0.01421	0.8108	4.17
Totals					100

Table 7.1: Failure Information for both Karabiner Types under Static Closed Gate Loading

Karabiner	**Primary Failure Position**	**Stated Failure Load**	**Failure Load**
Clog C1	Hook	23kN	25.6kN
Clog C2	Hook	23kN	25.2kN
DMM C1	Upper Radius	24kN	22.1kN
DMM C2	Hook	24kN	22.0kN

Table 7.2: Maximum Strain experienced in DMM and Clog Karabiners in Static Closed Gate Conditions

	Micro Strain at Failure in Closed Gate Position				
Karabiner	**Inner Shaft**	**Outer Shaft**	**Lower Radius**	**Top Radius**	**Gate**
Clog C1	11 900	-5280	-	3910	1030
DMM C1	6040	-4680	-2210	-167	-

Table 7.3: Failure Information for both Karabiner Types under Static Open Gate Loading

Karabiner	Primary Failure Position	Stated Failure Load	Failure Load
Clog O1	Back Bar near Lower Radius	7kN	7.57kN
Clog O2	Back Bar near Top Radius	7kN	7.4kN
DMM O1	Back Bar near Top Radius	10kN	7.75kN
DMM O2	Back Bar near Top Radius	10kN	7.63kN

Table 7.4: Maximum Strain experienced in DMM and Clog Karabiners in Static Open Gate Conditions

	Micro Strain at Failure in Open Gate Position				
Karabiner	**Inner Shaft**	**Outer Shaft**	**Lower Radius**	**Top Radius**	**Gate**
Clog O1	20 400	-14 100	-	-6350	-
DMM O1	40 900	-30 500	-6360	-6000	-

Table 8.1: Maximum Strains experienced during Dynamic Loading

	Micro Strain	
Dynamic Mass Applied	**Clog Karabiner**	**DMM Karabiner**
17kg	2735.12	3196.14
37kg	3199.51	3867.92
57kg	3672.26	4433.54
77kg	4065.61	5630.439
27kg (open gate)	5022.766	6482.13

Table 8.2: Comparison of Strains for Static and Dynamic Testing

Force Applied (N)	Clog Dynamic Strain	DMM Dynamic Strain	Clog Static Strain	DMM Static Strain
1560.45	2735.12	3196.14	1250	1311
2741.24	3199.51	3867.92	2270	1953
3991.93	3672.26	4433.54	2670	2842
4722.53	4065.61	6482.13	2900	3640