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Analysis of Rock Climbing Falls with Different Rope Paths

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1 Abstract

This study investigates how different rope paths could prevent high forces being exerted on the climber and the belay points that hold the rope beneath them. As climbers improve their technical ability to climb a cliff face, they will tackle increasingly more difficult climbs to test themselves to their limit. In these circumstances, it is likely that a complex rope path will come as a result of the climber having to find the best route for them to climb the mountain face [1], as there will be fewer cracks and ledges to hold on to. Therefore, this investigation will show how different rope paths will create a varying degree of loads on the belays points and the climber, if the climber happens to fall.

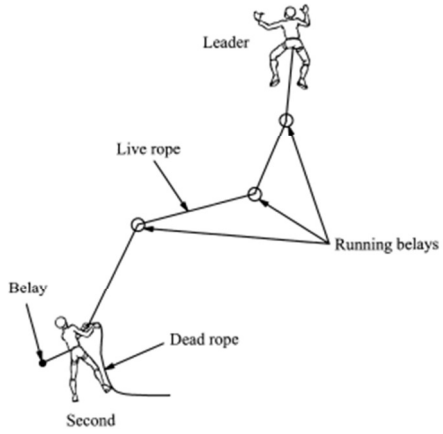
This experiment hopefully will give a better understanding of the forces present during climbing falls, as the current industry standard only tests a rope over a single belay [2], with the falling mass representing the climber descending directly downwards, with no trailing rope path.

1.1 Project Aim

The aim of this study is to create a representation of the forces present during a climbing fall. Each climbing rope undergoes stringent tests which ensure the best possible safety of the climber in a number of different situations, though little research has been made into the rope path the climber takes when navigating the cliff face other than 'M J Pavier's' work [1], and how this affects the force in the belay points and the climber themselves. Since there are various sizes of devices that create belay points on a mountain face, which naturally differ in strength according to size, this study should give a good insight into the different placements of safety gear. Further analysis will come from calculating the elongation of the rope after numerous tests, and how the performance of the rope changes accordingly.

1.3 Background

Rock climbing is a popular sport throughout the world. In the last 25 years it has seen a rapid increase in popularity [3], with more climbers embarking on more difficult climbs as climbing equipment improves, increasing the chance of injury as more risks are taken. A similar investigation conducted by 'M J Pavier' [1] highlights the stresses through the rope during a fall, where the life span of the rope can be determined by the tension it has been exposed to. A typical climb is drawn below to understand how an experienced climber would navigate a mountain face:



(Figure 1.3, redrawn from M J Pavier)

The diagram shows what is known as lead climbing, where one climber stays below whilst following the lead climbing and providing the 'anchor' if the lead climber were to fall. The person providing the 'anchor' is referred to as the second. The second will harness themselves to an anchor which may take the form of a metal shackle already attached to the rock or a metal spike that has been wedged into a crack by the climber. This process can progress when the lead climber can find a safe place to belay, allowing the second to climb the mountain themselves, with the lead climber taking responsibility of the rope. An experienced climber will most likely have a series of falls in the same place where there is a very demanding section of cliff face. In order to continue the climb, this section of rock face will be tackle at different angles in order to negotiate a way through. The climber may also risk having a greater belay distance than they are usually comfortable with since there is a lack of anchoring points. Increasing the distance that a climber would fall if a fall were to take place increases what is known as the fall factor:

$$\text{Fall Factor} = \frac{\text{Distance Fallen}}{\text{Length of Rope Involved}}$$

The fall factor [4] is a gauge of the severity of the force experienced by the climber during a fall.

From 'The Handbook of Climbing' [5], it gives a rough estimation of how a selection of commonly used knots effect the overall strength of the rope:

- Unknotted (100%)
- Figure of 8 (75-80%)
- Bowline (70-75%)
- Overhand (60-65%)

2 Rope Testing

The dynamic single rope used in this test has the following standards [5]:

- Diameter: 10mm
- Number of UIAA Falls: 6
- Dynamic Elongation: 36%

In order to gain a further understanding of the rope that would be used for analysis, a series of tests were performed to see how much force could be transmitted through the rope before it reached its breaking point. From previous research [4}, the breaking strength for a 10mm dynamic single rope would be approximately 2000 kg. For each test, a 3m sample of rope was cut from an original 70m length. A clean cut of the rope was made using the 'hot knife' - which prevented the rope from fraying at the end - ensuring it kept its structural integrity. To achieve a high level of accuracy, four identical tests were performed. The tensile machine used during this test utilised a high torque gearing system which allowed the machine to exert an extremely high force on the rope as it elongated it to it's breaking point. Each end of the rope was secured with a metal clamp, with each test taking over 10 minutes due to the low gearing that was required to elongate the rope. 'Figure 2' demonstrates the procedure:

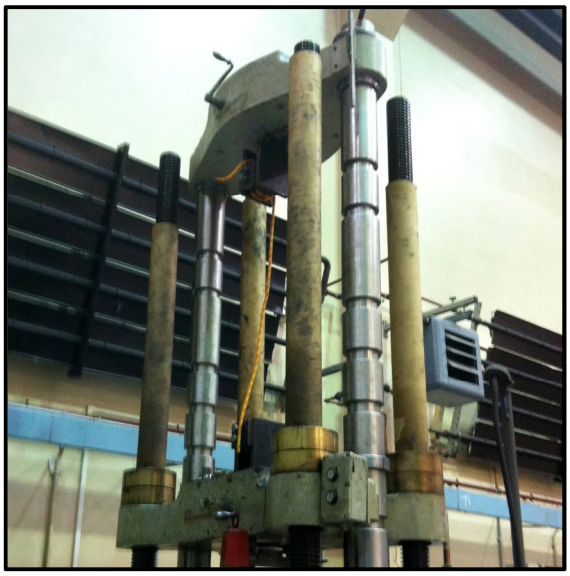


Figure 2

Unfortunately, the first test was inconclusive since the clamp at the top of the rope before the breaking point. However, the next three all gave results within 13 kg of each other, resulting in an average breaking strength of 2450 Kg, 450 Kg greater than expected [5]. Since the second, third

and fourth test were closely matched, it was decided that repeating another test to compensate for the failed first test was unnecessary.

3 Test Rig

One of the key areas of this study is to create an accurate representation of a climbing fall. Considering the average weight of a male adult is approximately 75 Kg in the United Kingdom [7], a construction of high structural rigidity and strength was required. Figure 3 [8] illustrates the final frame:

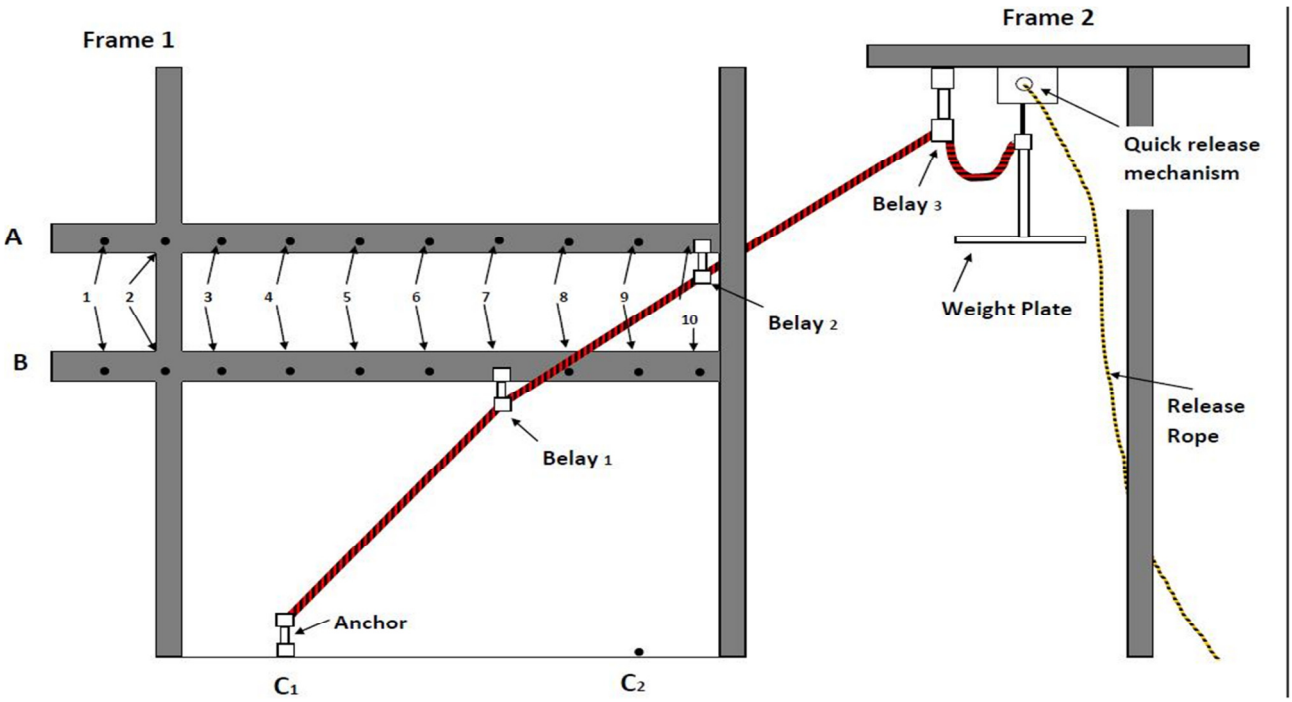


Figure 3

3.1 Procedure

- A specimen of rope was cut to the desired length in order for it to complete the necessary rope path.
- The belays on bar 'A' and 'B' were positioned to give the required path in which the rope would take.
- The mass was lifted into position with the quick release mechanism in the closed position.
- The rope was tied off at each end.
- The LabVIEW software was enabled with the release of the test mass occurring approximately 1 second later.
- Results from LabVIEW were plotted after a 4 second test interval.

3.1.1 Quick Release Mechanism

In the interest of safety, a mechanism had to made that was able to release the test mass from a given height without endangering anyone. The release had to be instantaneous to ensure the mass was not obstructed on it's descent, and be reliable and simple to configure to allow the user to conduct numerous tests in the shortest time possible.

3.1.2 Karabiners or D-shaped Shackles

D Shaped shackles were preferred to karabiners as it was easier to fit the load cells on a toggle bar between two d-shaped shackles rather than a karabiner. The outer radius of the d-shaped shackle [9] exceeded that of a standard karabiner so there was less probability of the rope fatigue, as research [10] has found that a rope will not fail unless subject to a sharp edge or acid corrosion.

3.1.3 Testing Load Cells

In order for the load cells to work with their corresponding computer program and give accurate results, they needed to be calibrated. In order to reduce time calibrating each individual cell, each load cell was connected in line and loaded simultaneously. A varying force from 0 kN to 5 kN was applied across the load cells with the microstrain of each cell noted at each separate load ratings.

3.1.3 LabView

LabView 8.5.1 was selected as the software that would record the data that was being fed to it by the various load cells. LabView is able to compute data over 0.01 second intervals, with the total test time set at 4 seconds.

4 Results

4.1 Setup 1

For the initial set of results it was necessary to begin with a baseline test to ensure that the equipment was working and not to over complicate the procedure during the first stages of testing.

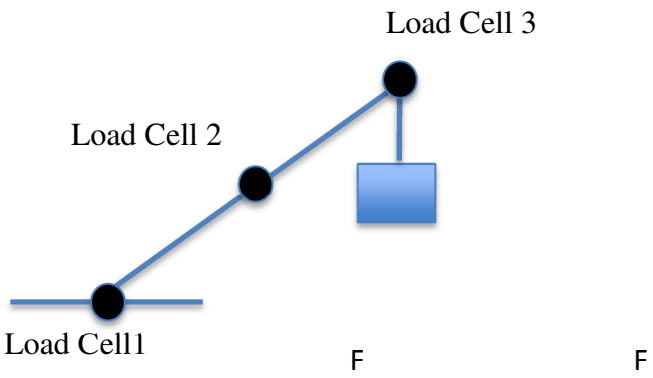


Figure 4.1

'Load Cell 1' represented the belay at the bottom of the rope where it where it was anchored to the floor, 'Load Cell 2' a midpoint belay and 'Load Cell 3' the nearest belay to the climber. With a 30kg mass dropping from a height of 1m and the total length of rope equaling 4m, a 0.25 fall factor was achieved. This would be considered a gentle fall when climbing [5], with most climbers avoiding a maximum fall factor of 0.3 between belay points if a fall was to occur.

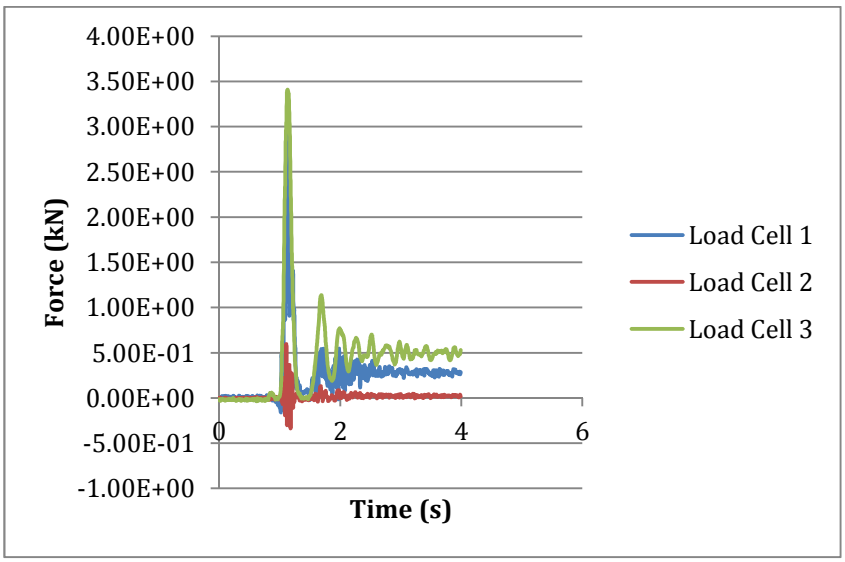


Figure 4.1.1

From the ‘Figure 4.1.1’, plotting the force of the various load cells over a four second period, there was a spike of force at approximately 1.1 seconds as the mass descended to its lowest point before the rope resisted the force. The peak force for ‘Load Cell 1’ was 3.2 kN, ‘Load Cell 2’ 1kN and ‘Load Cell 3’ 3.5 kN. It was expected that ’Load Cell 3’ would experience the highest force as some of the load would have dissipated through ‘Load Cell 2’ before reaching ‘Load Cell 1’, the anchor point. From research [3] it was established that a single rope as used in this test should prevent the climber from experiencing loads of 12kN and over, which all sets of load cell data fall below.

4.2 Setup 2

The diagram below represents the rope path for the second experiment:

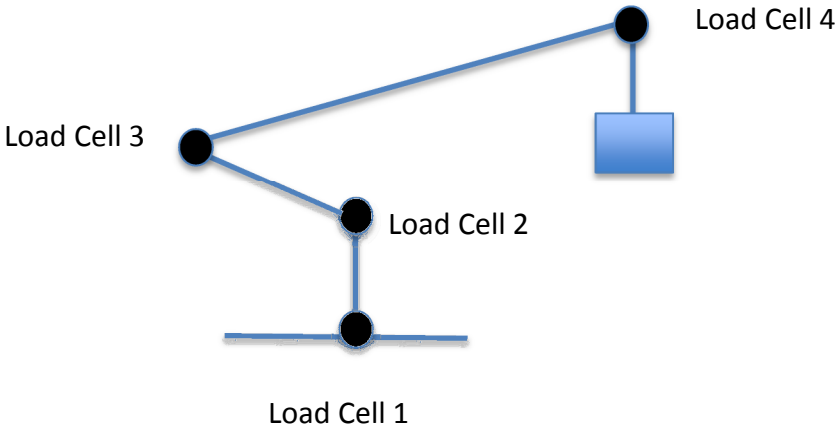


Figure 4.2

Using the same 30kg mass mentioned previously with test 'Setup 1', 'Setup 2' involves a more complex rope path with the addition of another load cell, resulting in the rope turning back on itself, a common scenario for many rock climbers. From 'Figure 4.2' it shows that the top load cell and the anchor load cell rope do not sustain the greatest load, with 'Load Cell 3' reaching a peak force of approximately 5.2 kN due to the rope turning on itself at this point. When compared to the results found in 'Figure 4', this shows a peak force increase of approximately 1.5 kN. The length of rope cut for this test totaled 4.5 m. With the fall recorded at 1.5m, this equates to a fall factor of 0.33.

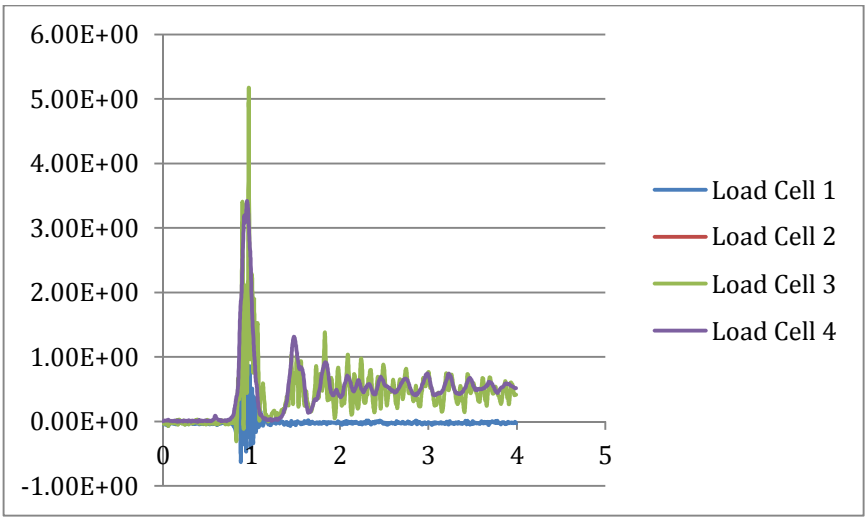


Figure 4.2.1

To give a better insight into the maximum force experienced at each load cell, figure 4.2.2 was constructed:

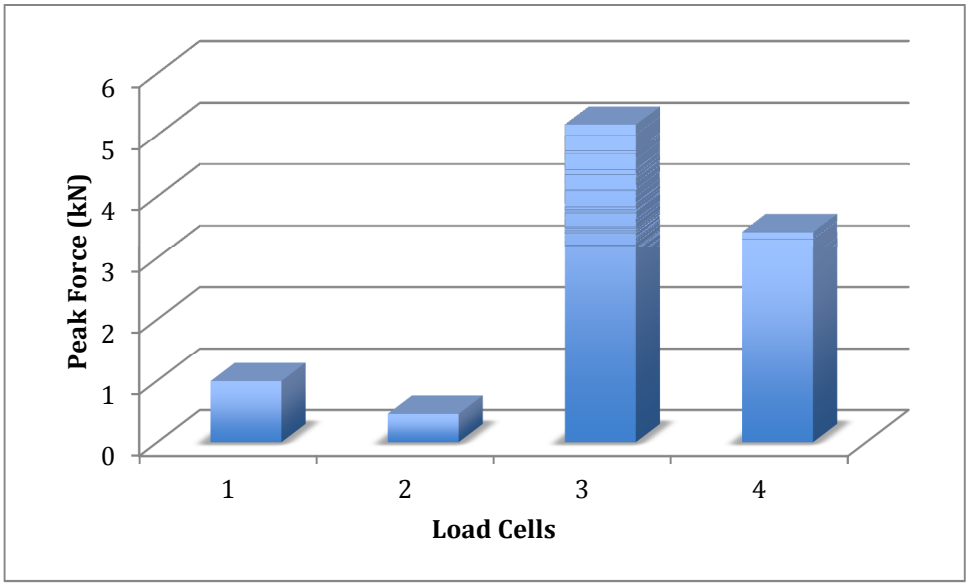


Figure 4.2.2

This shows a clear representation of the minimal force the anchor belay now has to sustain due to this particular rope path. The time at which each peak force occurred can be seen in table 4.2.3

Load Cell Number	Time of Peak Force (s)
1	0.91
2	0.99
3	0.97
4	0.95

Table 4.2.3

As expected, the peak force of 'Load Cell 4' is marginally before that of 'Load Cell 3' and 'Load Cell 2', though 'Load Cell 1' - the cell furthest from the falling mass - experiences a peak force after only 0.91 seconds. However, since the belay point associated with 'Load Cell 1' was connected directly to the rope, a shorter delay in tension would have occurred compared to the other three belay points, thus resulting in the shorter time period.

4.3 Setup 3

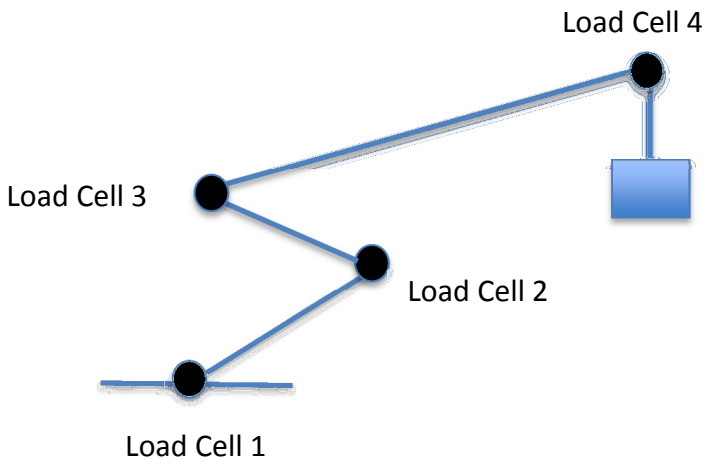


Figure 4.3

In this circumstance, the climber has created a zig-zag rope path as they have scaled a mountain face. With the results from 'Setup 2' illustrating how the majority of force is distributed through the upper belay points, this will give a further understanding on how little force finds its way to the lower and anchor belay with this zig-zag arrangement. To give a better representation of a real life climbing fall, the test mass was increased to 75 Kg to represent the average mass of an adult [7].

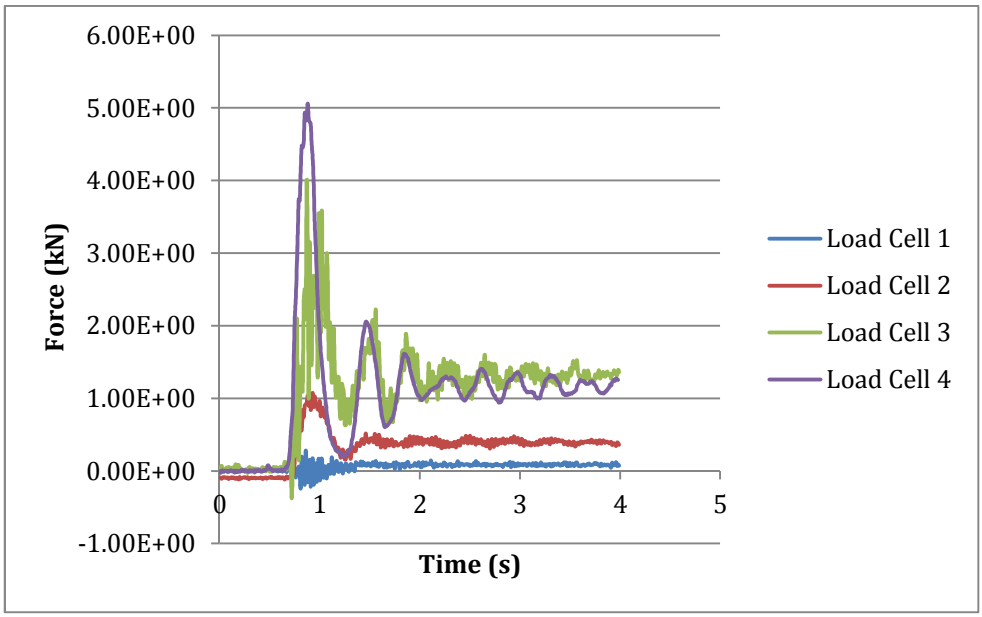


Figure 4.3.1

From the results there was a peak force on 'Load Cell 4' of approximately 5kN, similar to the peak force seen in 'Setup 2' even though 'Setup 3' has a 40 kg mass increase, with the fall factor remaining constant. Therefore the zig-zag rope path is more evenly distributing the force. To illustrate more clearly how the force was distributed, a separate bar chart was created:

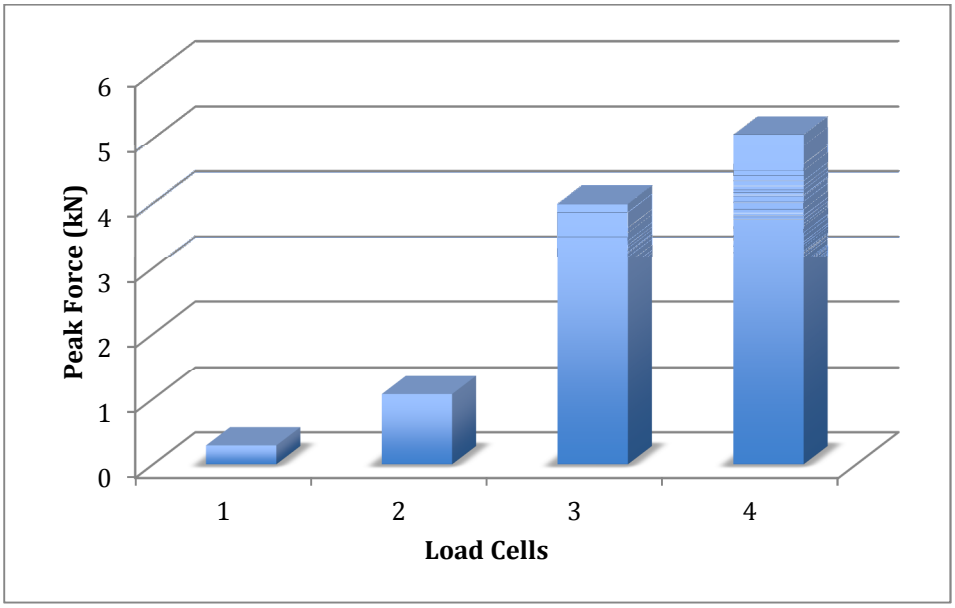


Figure 4.3.2

With this rope path, a general decrease in force is observed as it moves down from the top belay. The maximum force recorded at 'Load Cell 4' was recorded at 0.9 seconds with a value of 5.06 kN, with the anchor load cell experiencing a peak force of 0.278 kN at 0.86 seconds. As stated in the earlier setup, the anchor load cell was the first to experience its peak load due to it being tied directly to the rope. Once more, the force reduces significantly once an acute angle has been made in the rope path, with a peak force of 3.99 kN at 'Load Cell 3' and 1.07 kN at 'Load Cell 2', with this occurring at 0.86 and 0.9 seconds respectively. With the peak force recorded at 5.06 kN, this is significantly below the safety standard of 12 kN that all climbing ropes must abide to [11].

5 Rope Elongation and Fatigue

As a side study, the elongation of the rope was measured over a number of drop tests. With the UIAA safety test a measure [2] of the number of drops a rope can withstand with a fall factor of 1.78, this test would give an indication of the accuracy of the values given by the rope manufacturer. It is known from research [11] that the elongation of a climbing rope must not exceed 40%.

A simple drop test was performed as seen below with a 50kg mass:

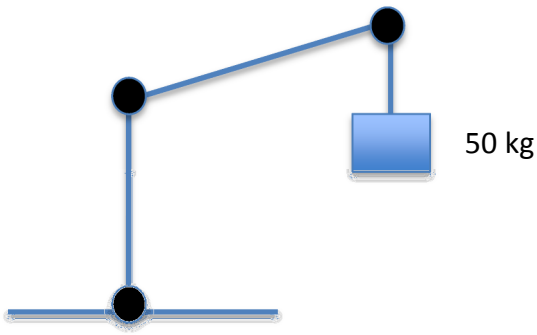


Figure 5

With the mass falling 100cm and the original length of the rope 496cm, the fall factor equated to 0.202. Table 5.1 lists the different values of elongation after each drop:

	Initial Length (m)	Final Length (m)	Elongation (m)
1st Drop	4.96	5.07	0.11
2nd Drop	5.07	5.16	0.09
3rd Drop	5.16	5.20	0.04
4th Drop	5.20	5.20	0
5th Drop	5.20	5.20	0

Table 5.1

The most severe change in elongation is during the first drop, with a value of 0.11m recorded. This is likely due to the fibres within the rope being exposed to their first high load value, resulting in any slack within the fibres to tighten. Referring to 'Design and Performance of Ropes for Climbing and Sailing'[12], climbing ropes have a number of different sections and fibres associated to them, so this tightening effect for the initial drop is highly probable. The second drop results in an elongation of 9cm, 2 cm less than that of the first test. Similar to the first, this will be the consequence of the fibres in the compacting together. The 3rd drop shows the elongation of the rope reducing more significantly as the rope reaches a state of equilibrium. This is shown from the 4th and 5th drop as the elongation of the rope remains at zero. The rope was checked after each test and no signs of fatigue (such as discolouring and bulges) were found. From previous research [13], there is a likelihood of an increase of load at the mass due to the changing load-extension relationship as the rope is elongated from its initial length.

6 Conclusions

Before research was carried out, it was naturally assumed that the final belay to the climber would experience the maximum force. However, as we have seen from the experimental setups as discussed earlier, the rope path that trials the final belay is fundamental in how the force of the falling mass is distributed. In ‘ Setup 1’, considering a simple rope path with three belay points, the peak force is similar for the anchor belay and the final belay, with the middle belay experiencing a small magnitude of force due to the straight rope path between the belay points above and below it. Due to this straight rope path, altering the distance between the belay points would have made little difference to the final results.

When considering a rope path that turned on itself, it illustrated how the anchor belay was under less load, alluding that the anchor belay would be of less importance than it would be when used to tether a straight rope path. However, the acute angle and increased spacing between the belays at the point at which the rope turned upon itself culminated in a peak force higher than that seen in ‘Setup 1’. With non-permanent safety gear such as cramming devices [5] more prone to failure when loaded sideways, it would be recommended that this type of climb would be safer where there are permanent fixed belay points which can withstand greater loadings. When considering ‘Setup 3’, the zig-zag path resulted in the upper two belay points taking the vast majority of the force. However, since the peak force seen in ‘Setup 3’ was very similar to that of ‘Setup 2’ it proves that the zig-zag rope path is effective at distributing the load and reducing peak forces.

As for the elongation and fatigue of the rope, it remained consistent over a series of tests once the fibres settled after the first few initial drops. This is expected [12] as rope technology has improved a great deal with advanced use of nylons and other synthetic materials to create a consistently safe climbing rope over a number of falls. This particular rope has UIAA [2] drop rating of 6, and considering this is under conditions of 1.78 fall factor and a 80 kg mass, the laboratory experiments were vastly less severe. In terms of improvement, it was difficult to gauge if the slack in rope was consistent when replacing it for each different rope path. Though two different brands of rope were used during the test, the differences between them was nominal. However, accuracy would have been increased marginally if the same rope was used throughout. As for the rope elongation, it would have been beneficial to attach a load cell in between the end of the rope and test mass to note the different values of load experienced after each drop.

7 Acknowledgements

I would like to extend my thanks to numerous members of senior university staff who made this dissertation project possible. Firstly, I would like to thank Dr McLaren for guiding and supervising me through various aspects of this project, whether it was report layout, finding materials or recommending different members of staff in the university to assist me with various problems I encountered during this research. Mr James Gillespie for assisting me in every practical drop test I did and setting up the 'LabVIEW' software before each day of testing. Mr Gerry Johnstone for advising me with regards to the risk assessment, Mr Andy Crocket for conducting the tensile test earlier in the semester which gave a baseline test for me to work with and finally Mr Chris Cameron for setting up the test rig in the James Weir building.

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