The Effects of Different Types of Damage on the Strength and Extensibility of Climbing Ropes

Technical Paper

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Abstract

Ropes must be able to take the weight of a climber in a fall without failure or transmitting too great a force to the falling body. Many within the climbing community are of the opinion that "ropes don't break", however work has been done previously which confirms ropes will break if they are damaged in particular ways. This project aims to determine how different types and severities of sheath damage affect the strength and extensibility of climbing ropes. Three types of damage were applied to the sheath: cutting strands, removing strands and abrading. Using tensile testing, it was found that removing strands from the sheath had the most significant impact on rope strength with the greatest number of strands removed decreasing the strength of the rope by 19%. Cutting all strands at a point in the sheath reduced the rope's strength by 15%. The method of abrading the sheath had a small but marked influence on both the strength and stiffness of the rope. Further testing is required to validate the results and dynamic tests should be performed to determine the safety of the damaged ropes in a fall.

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1. Introduction

Climbing has been popular as a sport for around 130 years [1] and is a risk activity. Ropes are the most important piece of equipment available to climbers and as such, they must be able to withstand the forces generated in a fall in order to be adequate safety devices for the climber.

Early ropes were made from natural materials such as hemp, silk and manila. Although these ropes were generally safe enough for top roping, they provided inadequate protection for the more dangerous lead climbing.[2]

The 1950s saw the introduction of dynamic climbing ropes made from Nylon. Polymeric fibres have very high strength parallel to their longitudinal axis so they are ideal for ropes which are subjected to high tensile loading. Almost all ropes have a kernmantle design, illustrated in Figure 1.

The core provides the main strength of the rope, whilst being protected by the outer sheath. The core has a complex structure, comprising a number of cords twisted around each other. The cords themselves are made from intertwined strands and each strand is made up of tiny threads.

Figure 1: Kernmantle construction of climbing rope. Notice the coloured woven sheath surrounding the white twisted cords making up the core.

As well as high strength, elasticity is also an extremely important rope property. Elasticity is required for ropes to absorb the energy from a falling climber and dissipate it away from the body, as a force of 12 kN or more is found to cause internal damage to the human body.[2]

According to the BMC Summit article "Learning the Ropes"[3]; ropes must withstand five consecutive drop tests without failure. Under loading of an 80 kg mass, a rope's extension must not exceed 8%. While stiff ropes can be dangerous as they do not allow loads to be dissipated away from the climber, too much elasticity will lead to a bungee effect.

Manufacturers give recommendations for when to retire rope but these are very generous underestimates of the rope's life – a rope has never failed due to a manufacturing fault.[4] Results presented to the BMC Technical Committee Conference[5] showed that although ropes deteriorate over time, even a rope which was 29 years old did not break on its first drop test. Climbing centres such as the Ice Factor in Kinlochleven take a cautious approach to rope retirement. All ropes are checked weekly and lead ropes are downgraded to top ropes at the first sign of any furring. Top ropes are usually discarded after only two years.[6]

Work done by Pit Schubert in his years working in safety research for the DAV (German Alpine Club) [7] looked at rope failures in Germany and Austria between 1983 and 2002.[8] He found that there were no more than two rope failures in any year, even though there were hundreds of thousands of climbing falls each year. Schubert concluded that ropes will not break unless damaged.

The purpose of this project is to determine how dynamic climbing ropes behave under loading and how various types and severities of damage to ropes affect their extension and strength.

While it has already been established in previous work that ropes will not fail under normal loading conditions, only when damaged; the degree of damage required to make ropes unsafe is unknown and subject only to speculation. This project aims to establish when it would be vital to retire a rope.

2. Testing Procedure

The static tests were carried out on a Tinius Olsen 81000 tensile testing machine. Before testing, sections of rope were cut to length (using a hot knife to prevent any fraying or unravelling) and different types of damage inflicted on them. For each test, the rope was loaded into the machine and wound at both ends around metal drums (as shown in Figure 2) and then secured with a knot and metal clamp. Although the rope could not be secured without inflicting some degree of damage, winding the rope around the drums has less of an impact on the test results than if the rope was gripped at each end, as this would induce stress concentrations and could encourage the rope to fail prematurely.

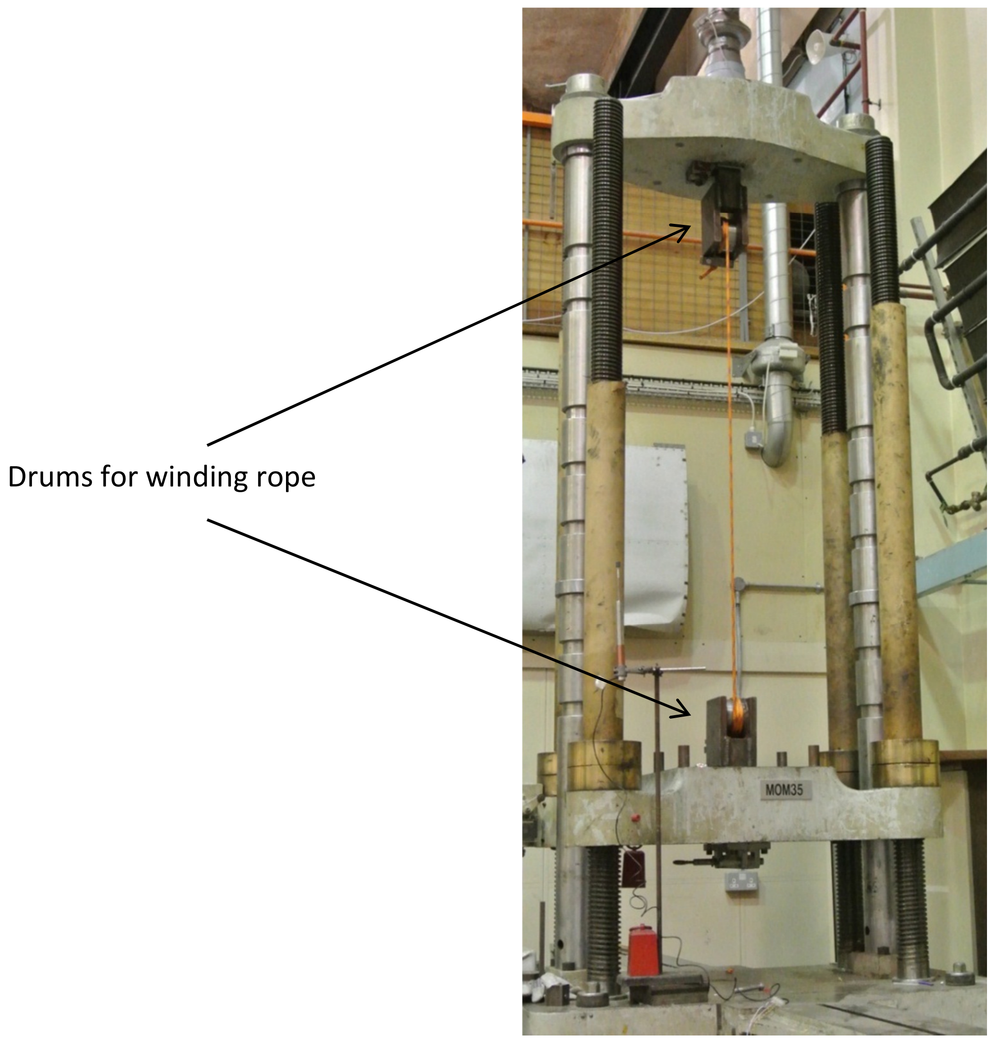

Figure 2: Tensile test in progress. Notice the rope wound around drums at each end.

Four baseline tests were performed to determine the breaking load required for a section of undamaged rope and to determine how the load in the rope varies with the rope’s extension.

The rope used had a pattern of coloured strands woven into its sheath: this was used to quantify the damage applied.

Each rope was given a unique code to identify the damage conditions applied to it. A detailed list of the ropes can be found Appendix A, Table 3.

Three types of damage were applied to the sheath and each type had a number of levels of severity:

- Cutting strands
    - Blue strands cut at a point on the rope
    - Red and blue strands cut at the same point on the rope
    - All strands cut at the same point on the rope
- Removing Strands (over two pattern repetitions)
    - Removing all blue strands
    - Removing double blue strand and single middle red strand
    - Removing all blue and red strands
    - Removing yellow strands
    - Removing all blue, red and yellow strands
- Abrading with sandpaper (over two pattern repetitions)
    - 50 times
    - 100 times
    - 200 times

Overleaf, examples of cutting, strand removal and abrasion are shown in Figure 3, Figure 4 and Figure 5 respectively.

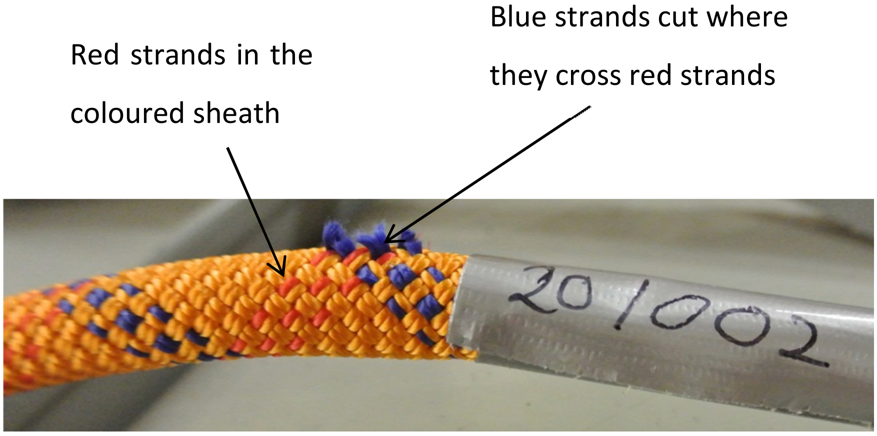

Figure 3: Blue strands cut at their intersection with the red strands at the midpoint of the rope

Figure 4: The red and blue strands and the yellow strands which ran alongside them were removed over two wavelengths around the midpoint of the rope

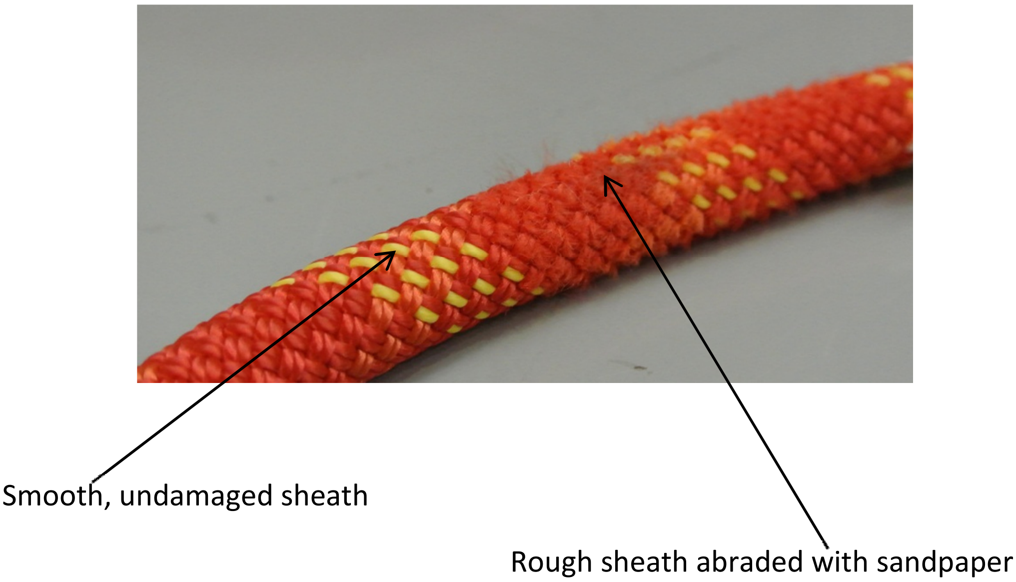

Figure 5: Rope abraded with sandpaper over two wavelengths around its midpoint

2.1 Sources of Error

As with all practical experimentation there are sources of error in the results obtained. Where possible, these sources were controlled to limit their effects. Potential sources of error in this investigation include (but may not be limited to) the following:

- Not having cut all pieces of rope to the same length
- Tying the sections of rope with varying tightness
- Temperature variations
- Inconsistencies in the damage application
- Using different ropes

3. Results

3.1 Baseline Tests

The results obtained determined how each section of undamaged rope behaved under static tensile loading. The machine measured the load in pounds and this was converted into Newtons. The breaking loads for each section were obtained, allowing a mean value to be calculated. These are shown in Table 1. The results also allowed the variation of load with extension to be plotted as can be seen in Figure 6, below.

Table 1: The breaking loads of each undamaged section of rope and the mean breaking load

Code	Description	Breaking Load (N)	Average Breaking Load (N)
10/001	Undamaged 1	22770	23910
10/002	Undamaged 2	24240	
10/003	Undamaged 3	24190	
10/004	Undamaged 4	24430	

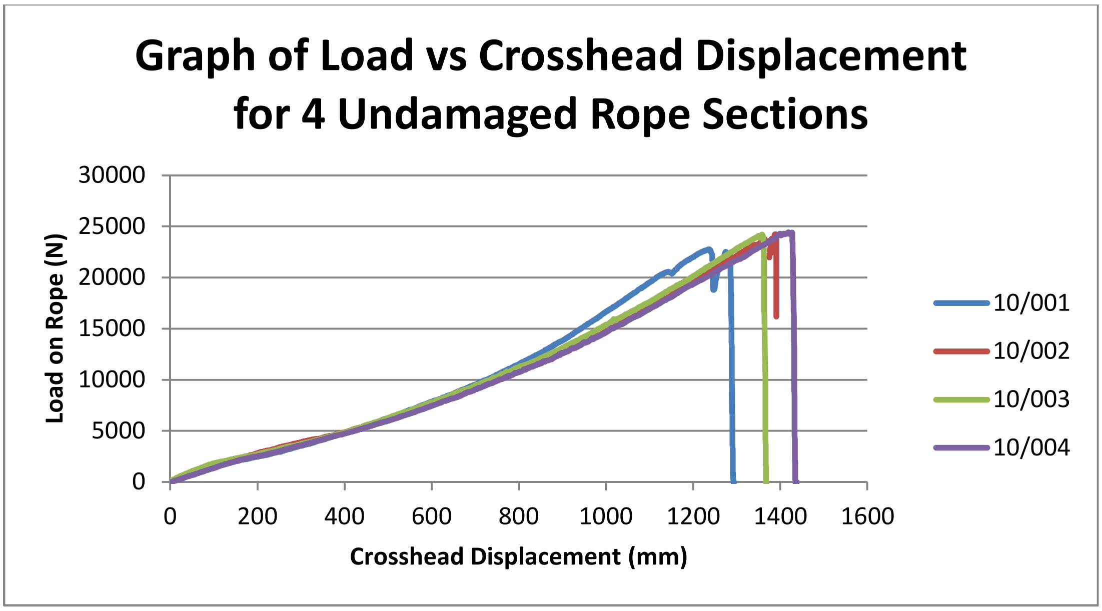

Figure 6: Graph of Load V Displacement for four sections of undamaged rope

The average load which could be withstood by all four rope sections tested before failing was found to be 23910 N – more than sufficient for holding the weight of a person.

When plotted, the relationship between load and displacement was almost linear to begin with, before curving upwards showing that the rope was becoming stiffer as the test progressed.

3.2 Sheath Strands Cut

Figure 7 illustrates how the results obtained from these tests compare with the baseline tensile tests performed. The baseline results are coloured green while the tests performed on ropes with a small number of sheath strands cut are coloured blue. The steeper curve of the blue lines shows that by cutting a few strands in the sheath, the rope becomes stiffer. There is very little change in the breaking load experienced by these damaged sections of rope over the undamaged rope – from the graph it can easily be seen that all sections broke around the 24000 N mark.

The red lines detail the results from the rope sections subject to more severe damage where all strands were cut at a point. Interestingly, the rope's stiffness was greatly decreased in this instance as can be seen by the shallower upwards curve. The breaking load of the sections severely damaged by cutting decreased by approximately 3700 N (15%) compared to that of the undamaged sections.

A comparison of the average breaking loads is shown in Figure 8.

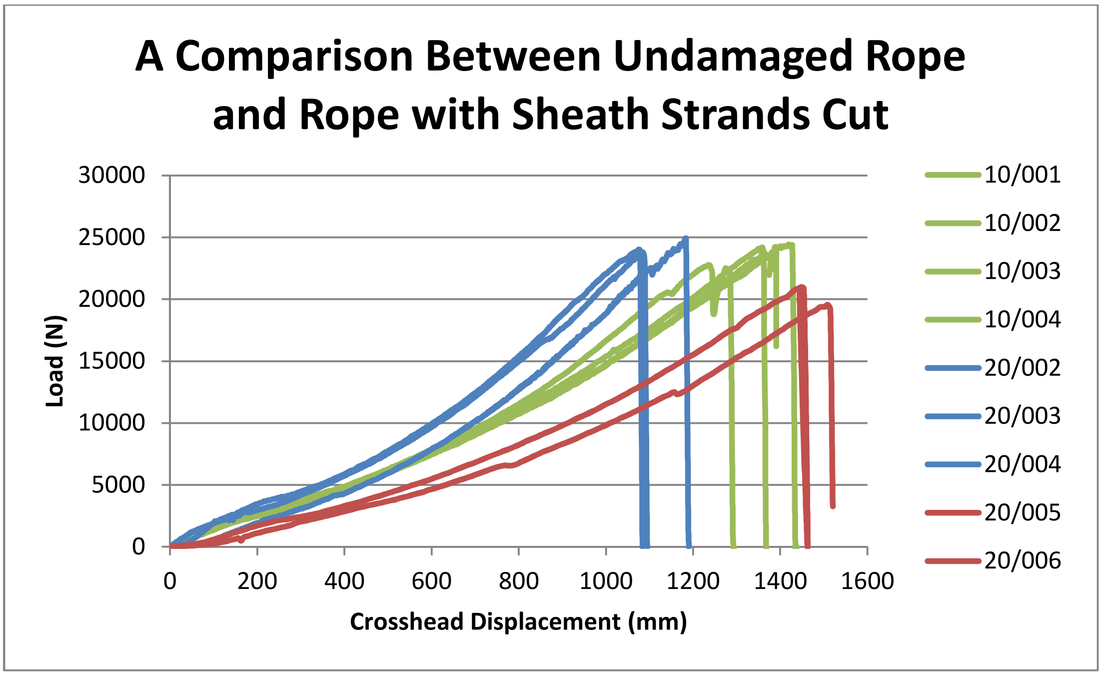

Figure 7: Graph comparing the results obtained from tensile testing rope with sheath strands cut against baseline tests. The baseline tests are coloured green while the sections with mild damage are coloured blue and sections with severe damage are coloured red.

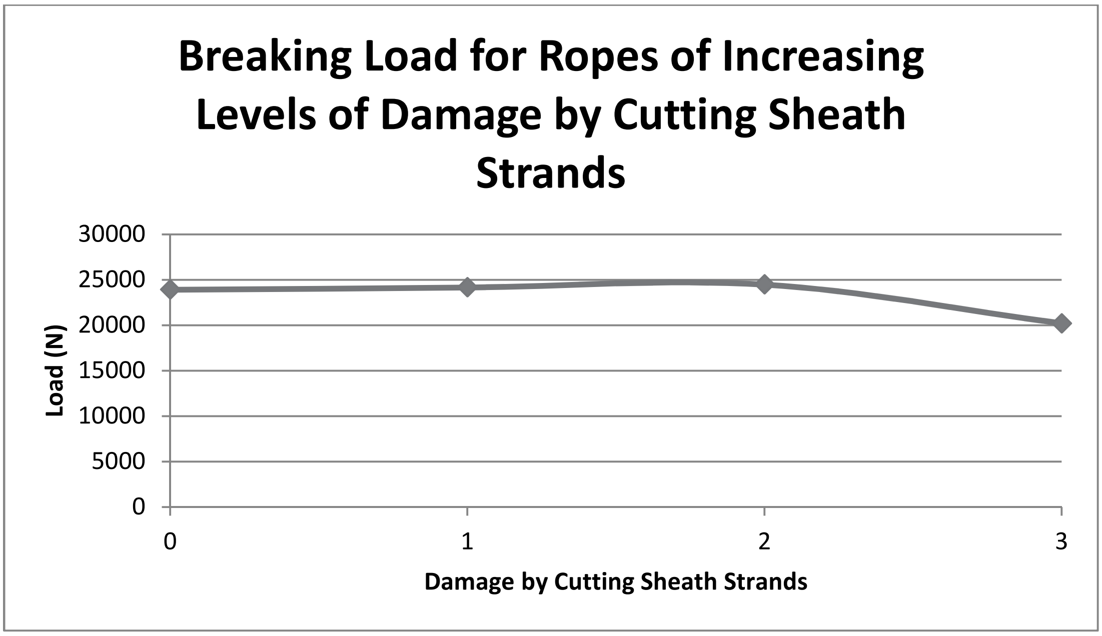

Figure 8: Graph showing the breaking load for different levels of damage by cutting sheath strands. 0 represents the average breaking load for the undamaged rope; 1, blue strands cut; 2 is the blue and red strands cut; 3 is all strands cut at the blue-red intersection.

3.3 Sheath Strands Removed

Figure 9 compares the tests carried out with sheath strands removed to the baseline tests. Again, the green lines represent the baseline results; the blue lines represent the initial mild damage by removing strands; the red lines, the severe damage where more strands were removed.

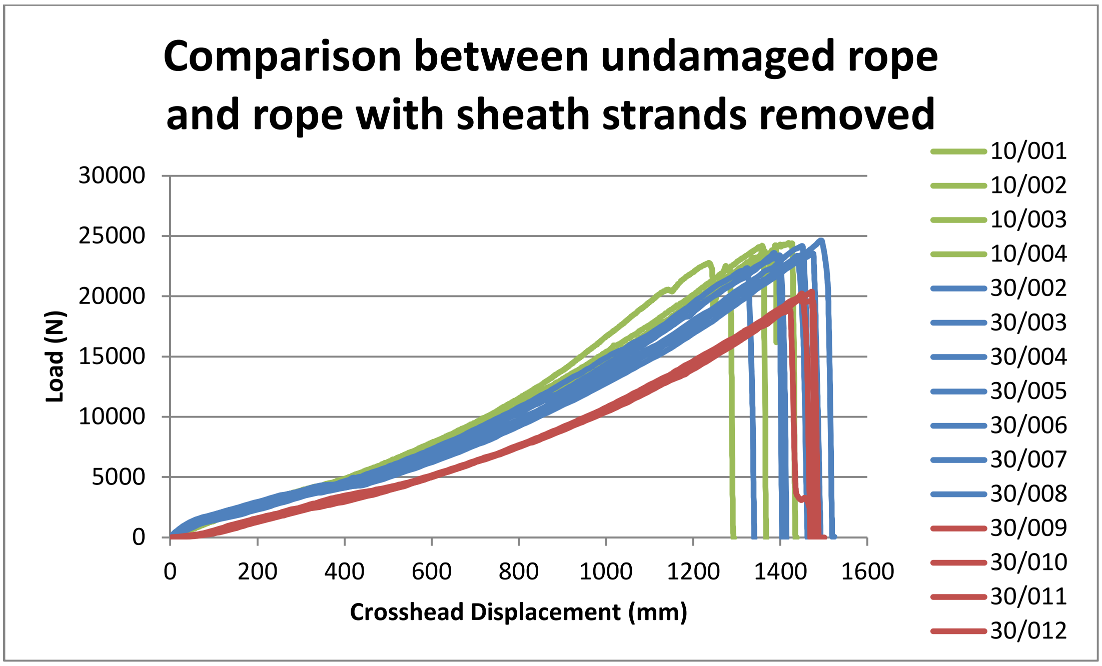

Figure 9: Graph comparing tensile tests of ropes damaged by removing sheath strands against those of undamaged ropes. Again, the results of the undamaged rope tests are coloured green, mild damage results blue and results from severe damage are coloured red.

Removing a small number of strands from the sheath decreased the stiffness of the rope by a small amount. Removing a larger number of sheath strands had a greater impact on the rope's stiffness.

For mild damage, there was no marked decrease in the breaking load; however for ropes with severe damage, the decrease in strength over that of undamaged rope was approximately 19% – larger than the decrease in strength generated by the most severe cutting tested. Figure 10 shows a comparison between breaking loads.

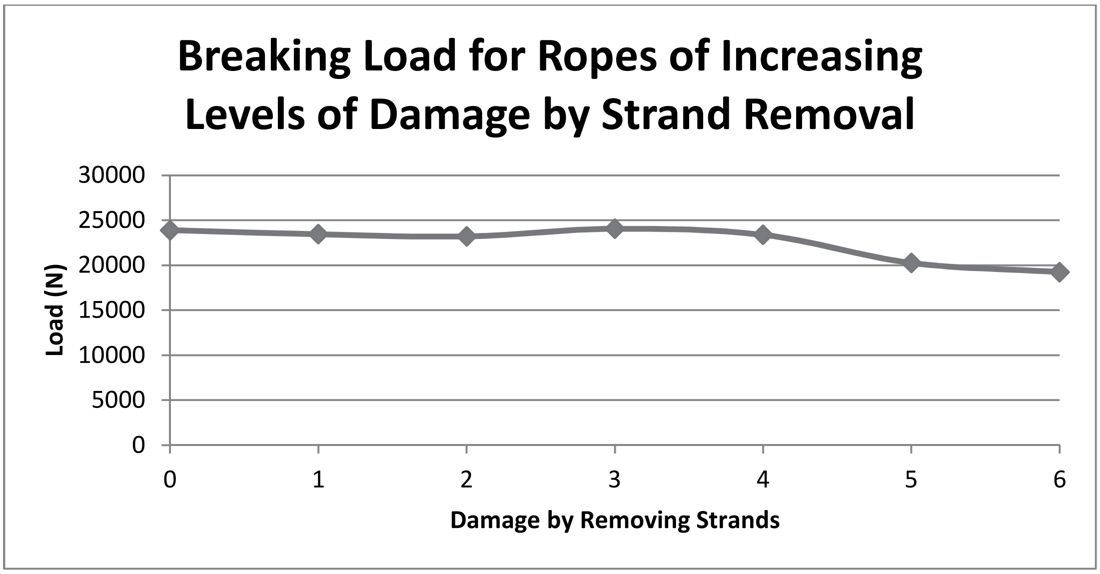

Figure 10: Relationship between removing strands from the sheath and the resultant breaking load of the rope. 0 represents the undamaged rope while 6 represents all red blue and yellow strands removed.

3.4 Sheath Abraded

Abrading the sheath did not have much effect on the ultimate tensile strength of the rope: the difference in breaking load between undamaged rope and the rope most damaged by abrasion was less than 2%. This small change in breaking load is shown in Figure 11, below.

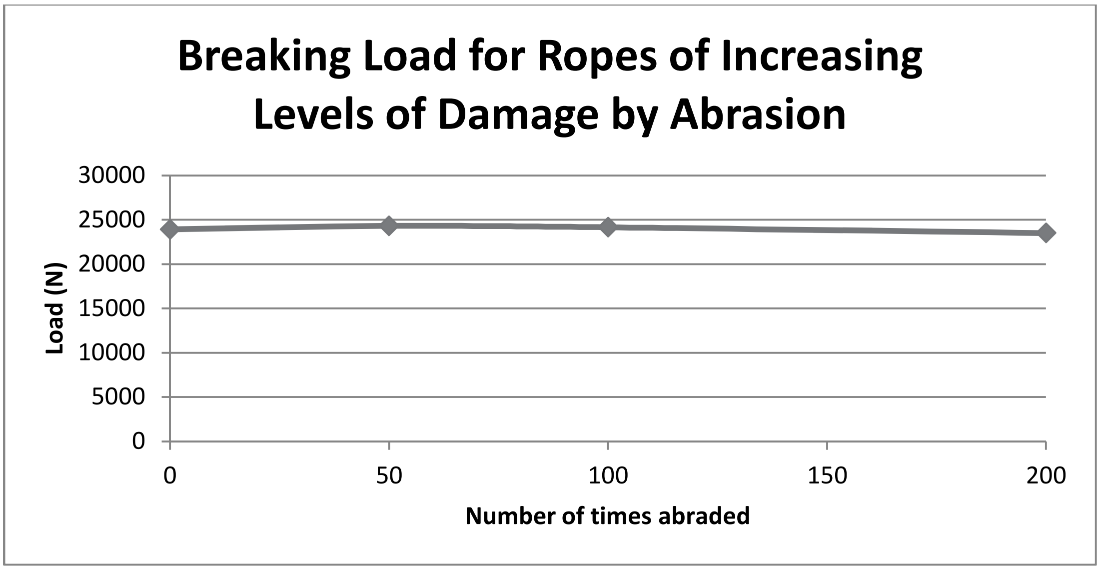

Figure 11: Graph showing how breaking load changes with the number of times the ropes were abraded

Figure 12 shows the results obtained in the abrasion tests next to the results from the undamaged rope tests. As established in Figure 11, there is little change in the breaking load however a change in stiffness can be seen. The rope appears to become stiffer as the severity of the abrasion is increased, however the damaged rope seems to be less stiff than the original undamaged rope. This could be attributed to a different rope being used in the abrasion tests due to running out of the original rope.

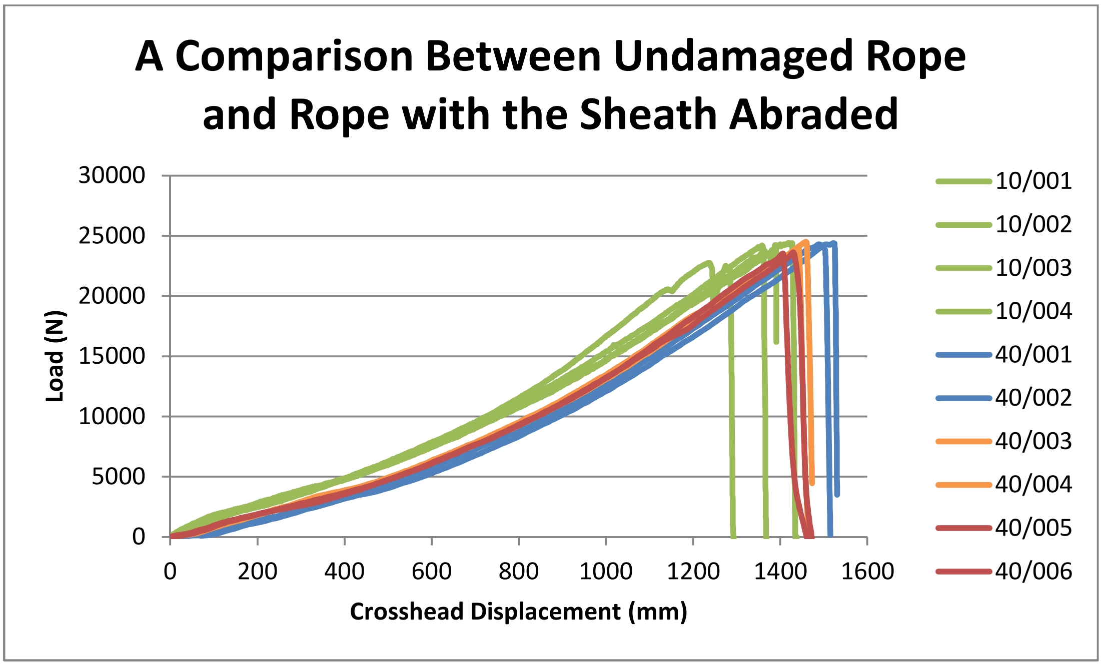

Figure 12: Graph showing the results from the abrasion tests against the baseline results. Undamaged ropes are shown in green; mild abrasion is blue; moderate abrasion is orange and severe abrasion is red.

3.5 Results Summary

Damaging ropes in different manners had different effects on their stiffness and strength; however, severe damage of any kind reduced the maximum tensile load the rope was able to withstand. Abrasion produced the smallest deviation from the strength of the undamaged rope, while the maximum number of strands removed produced the greatest deviation from the undamaged breaking load. Table 2 shows the rope efficiency of the most severely damaged ropes; that is, how their strength compared to that of the undamaged rope.

Table 2: Table of rope efficiency for the most severely damaged ropes of each damage type

Damage Type	Breaking Strength (N)	Rope efficiency (%)
Cut	20210	84.5
Removed	19250	80.5
Abraded	23500	98.3

4. Discussion of Results

4.1 Effects on Rope Strength

Removing a large number of strands from the sheath had the greatest influence on the rope's breaking load. This method destroyed more of the sheath than any of the others and left the core most exposed: it follows that the result obtained is logical. From Figure 10 (which compared the breaking loads of ropes with different numbers of strands removed) the drop in strength when large numbers of strands are removed is obvious; however, when removing different combinations of small numbers of strands there is some fluctuation in the breaking strength. Some of these differences could be put down to the spread of results expected between experimental tests (there almost a 7% difference between the strongest and weakest undamaged rope sections tested) but it is possible that the way in which the sheath strands are woven together provides strengthening properties. From the results it appears that disturbing the pattern in some ways may have a more significant effect on the rope's properties than others. As can be seen in Figure 4, removing a large number of sheath strands causes the core to zig-zag and this may increase local stresses, which would decrease the breaking strength.

When the tests were performed on ropes with some strands cut in the sheath, initially there was very little change in strength. Cutting more sheath strands led to the rope having a clearly visible decrease in strength. The results suggest that considerable damage to the sheath would need to be present for a rope to exhibit any substantial loss of strength. For damage of such nature to go unnoticed would be unlikely and as such, ropes with enough cut sheath strands would have been discarded before reaching this stage.

The strength of ropes abraded with sandpaper dropped by 2% on the average strength of the undamaged rope tested. While this seems disproportionately small compared to the reduction in strength from other methods of damage, the amount of damage itself was small. Abrading the ropes by hand proved difficult and after rubbing the sheath 200 times, the rope was still not in as poor condition as it had been when damaged by either of the other two methods. Figure 11 does show that the breaking strength was beginning to decrease with increased abrasion. With a better delivery method, more abrasion could be applied to the ropes in order to determine how substantial damage would need to be before the results were in line with those obtained from the cutting or removal tests.

4.2 Effects on Extensibility

Cutting sheath strands produced the most interesting results with regards to extensibility. When a small number of strands were cut, the ropes became stiffer and thus did not extend so far before failure; however when a larger number of strands were cut, the rope's apparent modulus decreased. These results are consistent with those obtained in work done on investigating the properties of a rope's core by John Allison in 2009.[9] Allison found that when one or two cords were removed from the core, the ropes became much stiffer under loading but then as increasing numbers of cords were removed, the ropes became less stiff. Allison put this down to the way the cords are intertwined within the core. He suggested the initial stiffening could be attributed to the new straighter alignment of the cords, and then put the loss of stiffness down to the reduction in material present in the rope. Cutting sheath strands may have a similar effect on the alignment of the fibres in the rope, causing it to exhibit similar changes in properties.

Increasing the number of strands removed from the sheath also decreased the stiffness of the ropes tested, although unlike the results obtained from cutting strands, there was no initial stiffness increase. The rope becoming stretchier could be linked to a reduction in material and possibly to the core becoming less constricted as it was no longer fully encased in the sheath.

While increasing the degree of damage by cutting or removing sheath strands ultimately reduced the stiffness of the rope, increasing the amount of abrasion to the rope made it stiffer. The results from these tests were the most consistent results achieved throughout the investigation, with the lines on Figure 12 almost completely overlapping for results of the same test type. While the results showed a steady increase in stiffness, the abraded ropes were still less stiff than the undamaged ropes. This is thought to be due to having resorted to using a different rope at this stage in the project. To confirm the results obtained from the abrasion tests, two options are available:

- Repeat the abrasion tests using the original rope
- Perform tests on undamaged sections of the new rope

4.3 Discussion of Project Overall

To validate the results, more tests should be carried out. For some tests, only one set of results was available which is not enough to confirm any relationships between types or degrees of damage and their effects on the rope's properties. This was due to the machine reaching its full displacement before the rope broke – the reasons behind this were human error: the rope was not secured tightly enough or it had been cut too long. Having more repetitions of each test (at least four as in the baseline tests) would allow rogue results to be eliminated and only the most consistent ones would be used to draw conclusions.

Ideally, the same rope would have been used for every test however this was not possible as the original rope was used up before all practical experimentation was complete.

To establish how the damage inflicted on each of the rope sections would affect climbers' safety, dynamic drop tests would need to be performed. Although it is clear that the most severe damage of each kind does affect the rope strength (in some cases by approximately 5000 N); without dynamic testing it is unknown whether this reduction in strength would be enough to cause failure during a fall or whether the effects on stiffness would allow the forces in a fall to be transmitted to the climber.

Conclusions

Different types of damage were found to have varying effects on the properties of dynamic climbing rope; however, increasing the severity of all damage types was found to decrease the strength of the rope sections tested. Cutting a small number of sheath strands increased the rope’s stiffness but had little impact on its breaking strength. Cutting a larger number of sheath strands at one point decreased the rope’s modulus as well as its ultimate tensile strength. Removing sheath strands made the rope stretchier from the outset but removing more strands decreased the rope’s modulus further and produced a greater reduction in strength. Abrading the outer surface of the rope appeared to make the rope increasingly stiffer and weaker. To validate the results, further tests should be carried out with more repetitions of each test type. To determine how the effects of these damage conditions would impact real rope performance, dynamic drop tests should be performed. These would better simulate the distribution of forces in a climbing fall and therefore would give a realistic representation of the safety condition of the rope.

Acknowledgements

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Appendix A

Table 3: Detailed list of all ropes including their code, damage description and breaking load

Code	Description	Breaking Load (N)	Average Breaking Load (N)
10/001	Undamaged 1	22770	23910
10/002	Undamaged 2	24240	
10/003	Undamaged 3	24190	
10/004	Undamaged 4	24430	
20/001	Blue strands cut 1	24520	24160
20/002	Blue strands cut 2	23790	
20/003	Blue and red strands cut 1	24020	24480
20/004	Blue and red strands cut 2	24930	
20/005	All strands cut at blue-red intersection	19550	20210
20/006	All strands cut at blue-red intersection	20860	
30/001	Double blue strand removed (2WL) 1	23550	23450
30/002	Double blue strand removed (2WL) 2	23350	
30/003	All blue strands removed (2WL) 1	22290	23200
30/004	All blue strands removed (2WL) 2	24120	
30/005	Double blue & reds removed (2WL) 1	23560	24060
30/006	Double blue & reds removed (2WL) 2	24560	

30/007 30/008	All blue & red strands removed (2WL) 1 All blue & red strands removed (2WL) 2	23490 23280	23380
30/009 30/010	Yellow strands (along red and blue) removed (2WL) 1 Yellow strands (along red and blue) removed (2WL) 2	20340 20180	20260
30/011 30/012	Blue, red and yellow strands removed (2WL) 1 Blue, red and yellow strands removed (2WL) 2	19690 18810	19250
40/001 40/002	Abraded 50 times 1 Abraded 50 times 2	24320 24290	24300
40/003 40/004	Abraded 100 times 1 Abraded 100 times 2	24420 23890	24150
40/005 40/006	Abraded 200 times 1 Abraded 200 times 2	23450 23540	23500