THE STRENGTH OF KNOTS IN DYNAMIC CLIMBING ROPE

Technical Report

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2007/08

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Word Count 2948

1 Abstract

Previous research into ropes and the factors which affect their performance within many applications has been both wide and varied. However despite the essential use of knots in many scenarios within the popular sport of climbing, limited research has been conducted into how the presence of knots affect the performance of the dynamic climbing ropes.

The aim of this study was to quantitatively assess through laboratory experiments how the tensile strength of dynamic climbing rope is affected by different knots and how this strength varies with the differing structure of these knots.

The tensile testing machine was specially developed in order to allow each test sample to be analysed accurately. Throughout the course of this investigation over 60 break tests were conducted resulting in a wide range of data being obtained. During the experiments the strength of the rope was the primary interest and this was assessed with various test specimens that incorporated different knots with and without their radii of curvature having being altered.

From these tests the strength of the rope was found to vary greatly with values between 40 and 85% of the maximum strength of the rope depending upon the knot and the radius of curvature.

2 Introduction

Ropes are life saving pieces of equipment which are predominantly taken for granted within many sports.

A great deal of research and development has been undertaken in order to produce the specialised ropes we see today which perform consistently to a high level without failing no matter what conditions they are used in. It has been being able to ascertain and understand these conditions and how they contribute to the modes of failure that has made this advancement possible. At present the vast majority of research has utilised sailing rope as the test specimens. Previous testing has ranged from, loading the rope in tension until failure occurs due to the limit load being exceeded, the effect of water absorption and the different coating which can be used to protect the rope fibres, to simulating the fatigue effects of running a specimen repeatedly through a winch set up as would occur in a real life sailing environment.

Katherine Milne [1] produced an extensive range of results and it can be shown from these that tying a knot within a length of sailing rope will have a considerable detrimental effect on the maximum breaking load of that rope. In addition, it was also established that the characteristics of each knot examined had a unique effect on the strength of the rope

It is surprising then that whilst such extensive research has been conducted with a view to analysing the various failure mechanisms within static sailing rope, little work has been carried out for the very different scenarios and responses encountered by dynamic climbing rope. Although it is generally accepted that there is a loss in the performance characteristics of climbing rope due to normal wear and tear, there is at present little data to support this belief and as such a lack of specific guidelines as to the safe operational life of ropes depending on the exact circumstances the rope has been subjected to.

3 Dynamic Climbing Rope

In mountaineering the single most important piece of equipment is the climbing rope. The highly technical construction of the modern rope means that it is able to withstand the incredible rigors that professional climbing routes entail. It must be able to endure excessive abrasion from sharp rock edges and through the common climbing techniques of rappelling and belaying whilst also coping with whatever the elements can throw at it. In outdoor climbing it is highly possible that the rope will come into contact with moisture either from contact with the terrain or directly from rainfall, as such it must be able to survive repeated wetting and drying and also possible freezing and thawing cycles, in addition to this the rope may be subjected to prolonged exposure to ultraviolet radiation (sunlight) [2]. Each and every one of these factors which the rope may suffer has to be dealt with incurring the minimal detriment to the rope in order for it to still be able to perform its primary function of protecting the climber in the event of a fall.

In order to guarantee a ropes ability to perform to the high standards needed to provide assurance that the rope is capable of ensuring the safety of the climber provided proper use of the rope, a set of safety standards was set by the Union Internationale Des Association D'Apinisme (UIAA) [3]. Any rope carrying this certification is guaranteed to meet all the minimum safety standards having been tested within a laboratory environment. The main criterion the rope must conform to, is that it must exhibit less than 12kN impact force and hold at least five "test" falls in order to meet the minimum standards required to be deemed fit for purpose.

The testing undertaken depends on the type of rope and the application for which it is intended. Examples of these tests are an impact force test, an eighty kilogram static elongation test and the number of falls which a rope can withstand before failure occurs. The impact force test is an accurate indicator to how much force a rope is able to absorb. The impact force is a measure of the maximum load which will be transmitted through the rope to the climber when the rope arrests a fall. Therefore the lower the value of this load the less severe the impact felt by the climber will be. The UIAA standard states that the maximum value permitted on the first test drop is 12kN for a single rope and 8kN for half ropes and the maximum elongation of the rope in order to absorb this force is 45% of its un-deformed length. The 80kg static elongation evaluates the percentage of a rope’s length that it will stretch when subjected to static loading. The UIAA test for this is to hang an 80kg mass from one metre of rope and the criteria which must be met or exceeded is that the maximum allowable static load stretch is 8% for single ropes and 10% for half ropes. In the UIAA falls held test an 80kg weight is dropped 5m on 2.8m of rope repeatedly at five minute intervals until the rope breaks. To meet the UIAA standard a rope must survive a minimum of five test falls. This test simulates a fall factor of 1.77 and is deemed as a severe climbing fall.

In addition to the UIAA standards all dynamic climbing ropes must adhere to and pass the relevant tests stipulated within British Standards, BS 3104 [4] and BS 892 [5].

4 Experimental Procedure

Firstly all rope samples were prepared into 2m, hot knife cut, lengths as a defence against the rope fraying or unravelling.

Each sample was then tagged with its own unique number so that each end could be easily identified after failure had occurred.

The samples were then prepared with the appropriate knot tied in preciously the same way so that only the metal rods if necessary need be inserted prior to testing each sample. These steel rods would be used to increase the radius of curvature and were rubbed down with emery paper and then washed to ensure all sharp edges and grit were removed prior to coming into contact with any rope sample.

The appropriate sample was then inserted into the tensile testing machine (figure 1).

Figure 1:-Testing Setup

This method depended upon the supports which were required for each individual sample. In the case of the drum support(s) the rope was wound twice around the drum section figure 3 and then secured between two bolted plates and an overhand knot formed in order to prevent the rope slipping. The other method used was for knots which had a loop on one end and these were simply restrained with a shackle figure 2.

The external data logger was then calibrated and the analogue load dial and elongation plotter both zeroed. The test was then initiated and loaded to a value of one thousand pounds force (4448.22N) and stopped to allow the sample to be inspected for overall or knot slippage or other flaws which may have affect the validity of the results. If deemed suitable to continue the machine was then restarted and the appropriate test sequence completed.

Figure 3:- Drum Support

Figure 2:- Shackle Support

Furthermore if the test required the insertion of one of the steel rods within the knot, care was again taken to ensure that it was positioned exactly the same each time. This meant that the maximum distance was between the edges of the rod and the knot to further decrease the possibility of the rod cutting into the rope.

A separate length of rope was also used in order to constrain the rods so that when failure occurred there was no risk posed to the other laboratory users. It was made sure that this rope allowed the rod to rotate and translate as it would when completely unrestrained and also did not interact with the test rope sample.

Once failure of the sample had occurred the appropriate data was noted, the destructed sample removed, stored and then the machine was reset in order for subsequent tests to be completed.

5 Results and Discussion

Table 1 states the exact rope and knot pairing which were used within each test series.

Test Series	Rope Type	Knot Type
A	10mm Dynamic Climbing Rope	None/Bowline/Dbl Fig 8
B	12mm Static Sailing Rope	None/Overhand/Overhand +12.5mm rod
C	10mm Dynamic Climbing Rope	None
D	10mm Dynamic Climbing Rope	Overhand
E	10mm Dynamic Climbing Rope	Overhand +12.5mm rod
F	10mm Dynamic Climbing Rope	Overhand + 25mm rod
G	10mm Dynamic Climbing Rope	Overhand +50mm rod
H	10mm Dynamic Climbing Rope	Multiple Loading + None
I	10mm Dynamic Climbing Rope	Multiple Loading + Overhand
J	10mm Dynamic Climbing Rope	Multiple Loading + Figure of 8 Loop
K	10mm Dynamic Climbing Rope	Figure of 8 Loop
L	10mm Dynamic Climbing Rope	Figure of 8 Loop + 12.5mm rod
M	10mm Dynamic Climbing Rope	Figure of 8 Loop + 25mm rod
N	10mm Dynamic Climbing Rope	Figure of 8 Loop + 50mm rod

Table 1:- Test Types

Series “A” and “B” were setup and performed so that the test procedure could be honed and also to establish whether the trends described by Milne [1] held for different ropes types and knot diameter. It was found that again the presence of a knot would lessen the tensile strength of a rope and that by increasing the radius of curvature of a knot the strength of that knot could in fact be increased as hypothesized by Suber [6]. Having realised that there were trends in the results the following test series were designed so that a great range of results were collated in order to best understand the behaviour of knotted rope.

From series “C” onwards the rope used was standardised and a Beal Tiger 10mm dynamic climbing rope was chosen the technical data of which is presented in table 2. It was found that under 1000lbs of loading (4448.222N) the average extension of the rope was 124mm and the average breaking load was 17733.579N.

	Beal Guaranty	Lab. Results
Impact Force	7.60 kN	7.50-7.60 kN
Weight per metre	61g	61g
Number of UIAA falls	7	7-8

Table 2:- Beal Rope Data

The chosen rope was a Beal Tiger [7] 10mm dynamic climbing rope and of the type and standard used by experienced lead climbers. Consequently this type of rope will be subjected to some of hardest and most technically demanding climbing routes and as a result will encounter some of the most severe falls.

Test series “C” was used as a baseline test. This basically means that each test section contained no knot and the average breaking load recorded could then be said to equal to the ultimate tensile strength of this specific rope. This value would be used as a gauge strength against which the other test samples could be rated.

Test series “D, E, F and G” were used to assess the strength of a simple overhand knot, overhand with a 12.5mm rod, overhand with a 25mm rod and overhand with a 50mm rod inserted respectively figure 4.

Figure 4:- Overhand knot with from left to right 12.5, 25 and 50mm rod inserted

Suber’s [6] hypothesis that the use of such a small, in terms of radius of curvature, would reduce the strength of the rope dramatically was proved to be correct with the average breaking load of the overhand knot, test series “D”, achieving only 11076.073N 62.458% of the baseline test. Series “E, F and G” obtained 74.812%, 77.508%, 78.794% of the baseline strength respectively. These results categorically prove that the radius of curvature of a knot is critical in determining the overall strength of the knot.

Test series “K, L, M and N” utilised a figure of eight knot formed with a loop (figure 5).

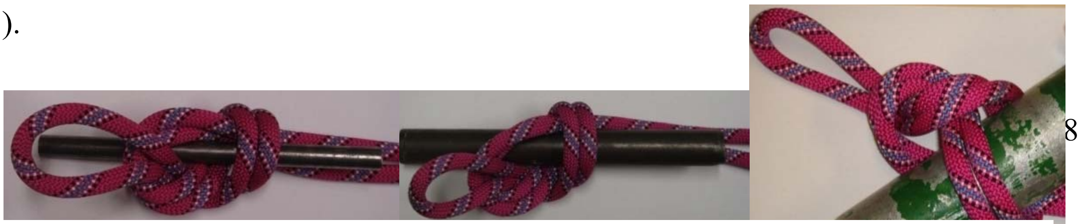

Figure 5:- Figure of eight loop with from left to right 12.5, 25 and 50mm rod inserted

This knot was chosen as it is a commonly and easily tied knot used by mountaineers when a rope is to be secured over an inanimate object. The formation of this knot also makes its structure very large in comparison to that of the overhand knot ≈ 6 times greater. As a result it was judged best to provide data from the opposite end of the spectrum and therefore provide the spread in results necessary so as to gain an oversight into the behaviour of loaded and knotted ropes. The baseline result achieved for this knot in series "K" was 84.155% of the straight rope baseline result. Series "L and M" obtained 89.120% and 91.743% respectively. These results again display that the radius of curvature is critical in determining the overall strength of the knot.

Consequently it can be noted that regardless of the specific knot tied within a length of rope the strength can be increased to a higher percentage of the baseline for that rope simple by adjusting the radius of curvature. However as displayed in test series "N", this increase can be too great and will in fact work to degrade the properties of the knot. This is highlighted by the results from the "N" test which only achieved 76.819% of the straight baseline result. A result which is greater than 7% less than the figure of eight loop achieved on its own.

Subsequently climbers should be made aware that for each knot there will be an optimum radius of curvature for each knot and care should be taken never to exceed this number.

Finally as climbers usually take a number of falls before replacing their ropes, the final series of tests were designed to assess the impact on the ultimate tensile strength this multiple loading scenario may induce. Test series "H, I and J" were used in order to assess the strength of, a straight unknotted length of rope, a length with an overhand knot and a length with a figure of eight loop inserted, when being subjected to multiple loadings. The following results were recorded for each test and each respectively rated 95.756%, 65.280% and 87.290% against the straight baseline result. Again the trend of a smaller knot will reduce the ultimate strength the most and the larger figure of eight achieving a value close to that of the unknotted rope. However when these values are compared to those from the baseline tests for each knot we can see that for the overhand knot the tensile strength has increased by 500.428N and the figure of eight by 556.033N.

As can be seen from figure 6, when the relative breaking load of each test series is plotted a linear chart is produced.

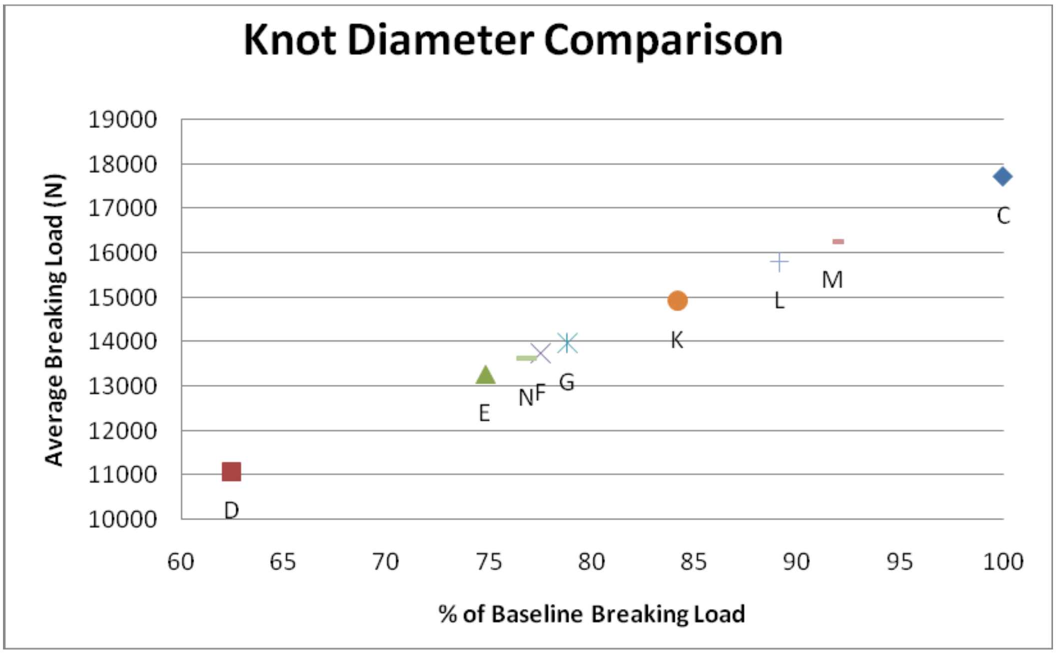

Figure 6:- Comparison of Knot Diameters and their respective strength

This is an interesting conclusion as it suggests that the strength of a knot is directly proportional to the diameter of the knot and consequently the radius of curvature of the knot formation.

Additionally it is also interesting to note that for all like tests the elongation response when subjected to loading up to the point of failure was identical when experimental error is neglected. This can be seen from figure 7 which depicts a sample from each test series conducted with the Beal rope [7].

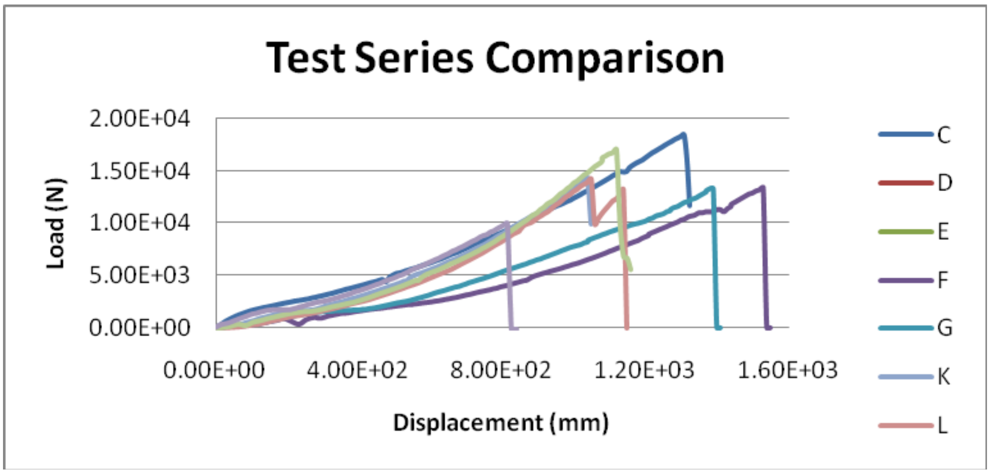

Figure 7:- Comparison of Load (N) v Displacement (mm)

6 Conclusion

The investigation of "the strength of knots within dynamic climbing rope" was carried out successfully. This is due to the extensive number of laboratory testing sessions that were conducted and therefore the quantity of results was large enough to enable specific trends to be witnessed. However not all areas were investigated as extensively as would have been ideal. This was as a result of the time and monetary constraints which were enforced on to the project. The time constraints were the biggest hindrance as on average the time required to take a sample through the complete experimental procedure would take in excess of 20 minutes.

Throughout the project any conclusions which have been made have been a result of repeat occurrences throughout the testing schedule and the trends which can be noted throughout the data which was recorded for each series of tests. The most significant observation which was made was that the presence of a knot no matter what size, shape or structure will decrease a dynamic climbing rope's ultimate tensile strength. Coupled with this fact is that the strength of each knot is dependent upon the magnitude of the radius of curvature of the first loop around the standing section of the rope. In addition the variation of the size of this loop can be used in order to find the optimum radius of curvature which will result in the optimum tensile strength of the knot being achieved.

Areas of which may be of interest for further future investigation have also been noted as follows:-

- Expansion of the data series recorded throughout this investigation.
    - Assessment of more knot types
    - Assessment of multiple knots within a length of climbing rope.
- The combination of knots and karabiners under tensile loading to assess whether this will further decrease the strength of rope.
- Analysis to find the optimum radius of curvature for specific knots.

It should also be noted however that the scope of possible investigations into this subject is vast and therefore the applicability and usability of possible future work should be considered before any work is undertaken.

7 Acknowledgements

The author would like to thank the following people, without whom this investigation would not have been possible. The project supervisor Dr. A. J. McLaren for his continued guidance, support and patience provided throughout the completion of this project. The University of Strathclyde store's manager Mr. J. Doherty for his enthusiastic support and help in sourcing and storing the materials necessary for the undertaking of the experimental procedures. Finally a particularly special thank you is extended to Mr. A. Crockett, Manager Materials Testing Laboratory, for his unstinting support throughout the many hours of laboratory testing and for the knowledge and experience which he brought to it which undoubtedly made the process faster and the repetition bearable.

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