The Strength of Climbing Ropes Loaded over Edges of Varying Radii

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28/03/2013

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Word Count: 2985

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200905518
ME409 Technical Paper

1. Abstract

Climbers routinely rely on climbing rope to ensure their safety in a fall situation. These dynamic ropes are of a kernmantle construction, with a sheath protecting the inner core strands. The ropes used are generally of very high strength, and do not tend to fail in normal use. When a rope does fail, it is almost always attributable to some unusual factor such as a sharp edge, the rope having been crushed or left wet, chemical or physical damage, or some combination of these types of issue. This project examines the effect of loading climbing ropes over an edge in terms of both direct strength, and lasting effects on the rope.

Rope samples tested over sharp edges showed a lower breaking load when compared to a baseline test, and exhibited a decreased stiffness. Pre-loaded ropes were also tested and it was shown that a pre-loaded and rested specimen will have a reduced breaking load, and increased stiffness. This increased stiffness depends on the magnitude of pre-load and does not appear to be a viscous effect- which is to say it does not return to its original stiffness over a period of time.

2. Introduction

In normal use climbing ropes are very unlikely to fail without an external factor. Typically rope failure is caused by pre-existing damage, chemical exposure or loading over a sharp edge. While careful storage and inspection can reduce the risk of chemical and other damage, sharp edges pose a very real problem for climbers. In a natural climbing environment there may be sharp rock present, which can be very difficult to anticipate or plan for. An older, worn karabiner or other piece of climbing equipment could well present a sharp edge, however appropriate equipment checks and procedure should provide adequate protection from this, whereas the naturally occurring sharp edge is a more unpredictable, and so more dangerous phenomenon.

The strength of climbing ropes over sharp edges has been known to be an issue since very soon after the introduction of modern kernmantle construction rope. Pit Schubert claimed that from 1968-2001 all climbing fatalities in Germany and Austria were due to sharp edges damaging the rope. (1). Some research was done by UIAA (the International Mountaineering and Climbing Federation, or Union Internationale des Associations d'Alpinisme) into establishing a standard of sharp edge resistance for climbing rope, however this effort was abandoned in 2004 due to difficulties in reproducing test results. (2)

Zanatoni and Henkel both performed studies into climbing rope behaviour over edges, however their works focussed on repeated loading of ropes over edges (3) (4). This project aims to examine the effect of varying the radius of the edge from 0.5mm to 1.5mm on the tensile breaking load of the rope in a double rope configuration. Some work was also done on the behaviour of ropes after a pre-loading over various edges and how their load paths differ from those obtained from fresh samples.

3. Kernmantle Construction Rope

Kernmantle construction ropes consist of a core of many twisted strands within a braided outer sheath protecting the core. Typically these ropes are manufactured from Polyamide 6 (5). Modern climbing ropes are highly over engineered and their manufacture is a complex process in order to produce ropes that can withstand the various environmental and operational conditions they are exposed to in normal use. Climbing ropes are extremely resilient; as they are often exposed to rain, snow, freezing conditions, thawing, UV radiation and many other degrading factors. Most of these conditions have stringent UIAA standards and regulations in place in order to regulate the risk to the climber.

3.1 Microstructure

On a micro scale, the modern climbing rope consists of polymer chains in a highly oriented structure. A polymer chain in a "relaxed" state is randomly coiled in an amorphous state. A system consisting of these unordered chains will therefore display isotropic behaviour. However, as the chains stretch out and align- such as in a fibre- this behaviour becomes anisotropic, with material properties dependent on direction.

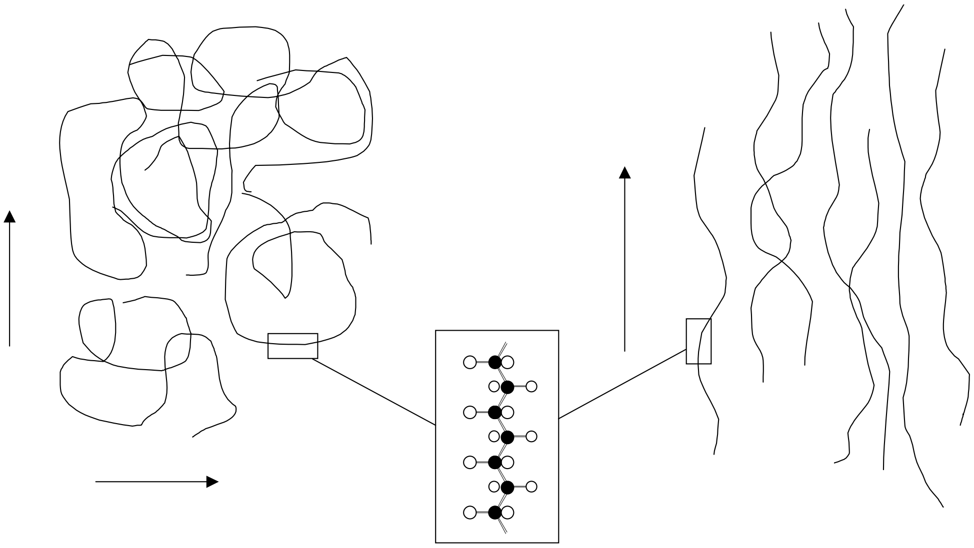

Figure 1 - Amorphous (left) and aligned (right) polymer chains (reproduced from (6))

Some polymers can also exhibit crystallisation, however full crystallisation is impossible as some chain ends etc. will continue to exist. Thus a semi crystalline structure forms, such as in polyamide 6 (6). Such a structure can then be drawn out into a fibre, causing the spherulitic crystallites to deform into micro-fibrils.

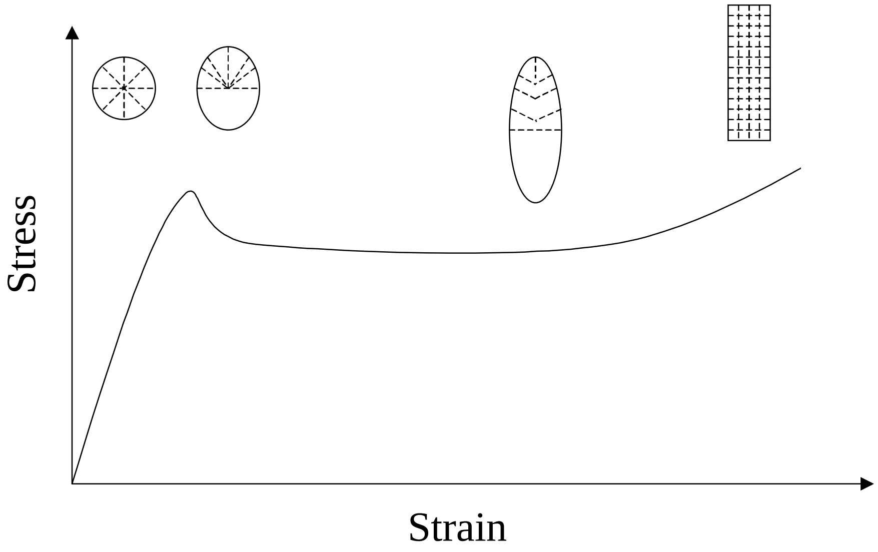

Figure 2 - Changes to microstructure of polymer during drawing (reproduced from (6))

As the polymer chains are oriented there are some amorphous regions containing the ends of chains, links between chains and closed loop chains. Of these, the links between chains are what provides the polymer with its strength along the length axis. As these chains are further aligned and stretched they eventually have no other way to dissipate the stress than to break. This happens initially in the shortest of the chains, and gradually the longer chains become taut and eventually fail. (7) (8)

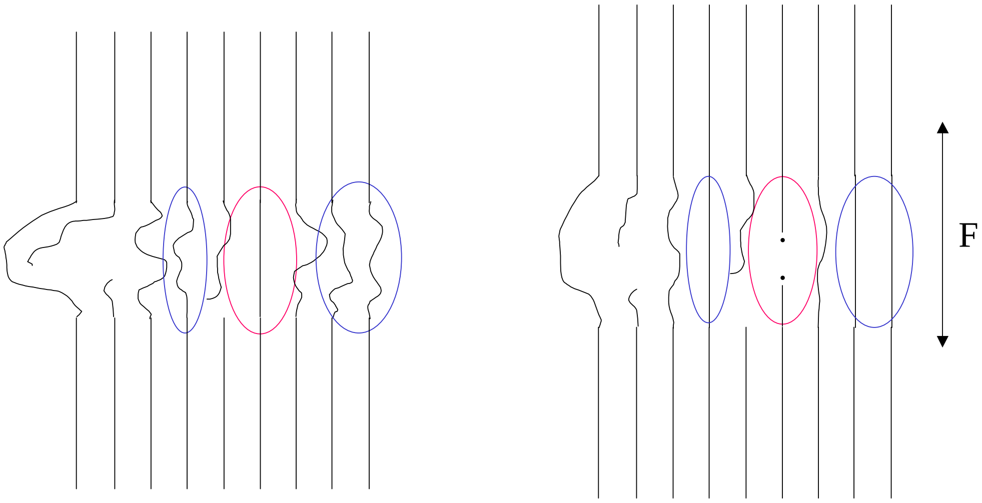

Figure 3 - Various chain ends and the effect of stretching (reproduced from (6))

4 Experimental Procedure

4.1 Preparation

Using PTC Creo 2.0 an edge holder and three sample edges (radius 0.5mm, 1.0mm and 1.5mm) were designed. These were then manufactured from mild steel by the James Weir M15 technicians. The bespoke testing rig was mounted in a Tinius Olson universal tensile testing machine, calibrated to BS EN ISO 7500-1.

4.2 Experimental Procedure

Samples of climbing rope were cut to length 2.4m using a hot knife. These were then loaded into the testing rig. Single rope configuration refers to a length of rope fixed at both ends. And double rope having both ends fixed at the top and running over the sharp edge within the rig at the bottom, see figure 4.

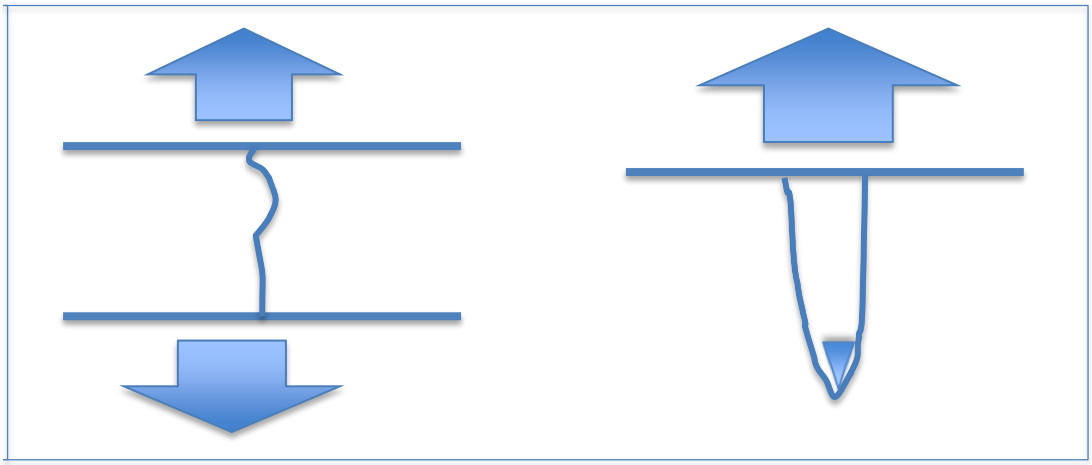

Figure 4 - Single (left) and double (right) rope testing configurations

The tensile testing machine then applied a force gradually extending the rope while recording both the force applied and the elongation of the sample. Initially a “blunt” edge was used, in this case an eye bolt, in order to establish values for the baseline tensile strength of the rope, and to give a control for comparison of the results over sharp edges. Then each sharpness of edge was tested, with all tests consisting of three samples being loaded to destruction. Load and displacement were both monitored throughout.

Further tests were performed to investigate the response of the rope to pre-loading to some proportion of its breaking load over specific edges (and in both baseline configurations). These pre-loaded samples were then tested to destruction in order to establish what effect the pre-loading had on their characteristics.

5. Results

Firstly baseline tests were performed in order to establish a control with which to compare other results. Both single rope and double rope configurations were tested to destruction. These tests established the strength of the rope experimentally, providing a control for further data.

5.1 Baseline Testing

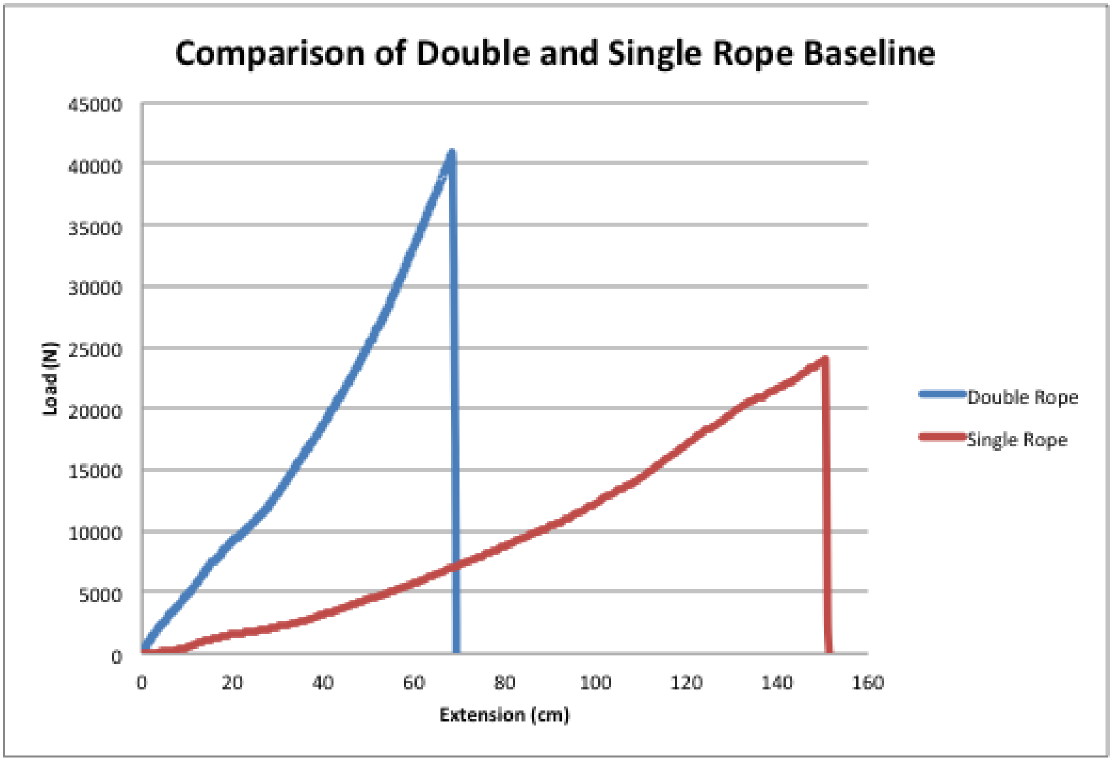

Figure 5 – Load extension curves of both baseline configurations

Figure 5 shows the load extension curves of both baseline configurations, the highest force followed by a rapid decrease represents the failure point of the rope. The double rope configuration is roughly twice as stiff as the single. This is because there is around twice the cross sectional area per unit length being stretched. The breaking load for the double rope is just over 160% of the single rope breaking load, presumably due to a minor stress concentration over the eye bolt (of effective radius 5mm).

5.2 Edge Testing

The manufactured rig and sample edges were then used to establish the breaking load and load path of climbing rope loaded over each edge.

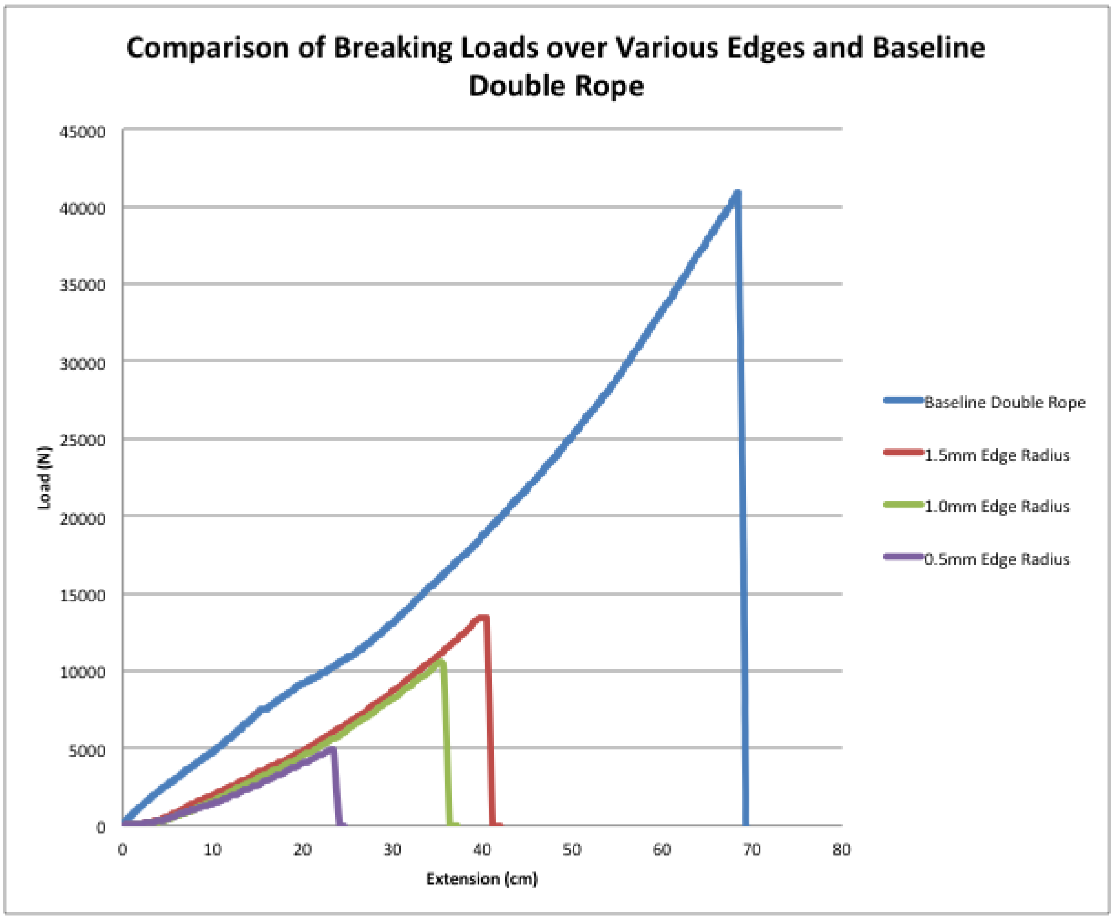

Figure 6 – Load extension curves of ropes loaded over each edge.

Figure 6 shows the behaviour of ropes loaded over each edge. It can clearly be seen that decreasing the radius of the edge- making it sharper- will lead to a decrease in the ultimate breaking load of the sample. Loading the rope over a sharp edge causes a very large decrease in breaking load, the 0.5mm radius edge reducing the ultimate strength of the rope by almost 90%.

It is worthwhile to note that these edges were manufactured and as such consist of fairly smooth surfaces and consistent geometry. In a real-world situation where a climbing rope is exposed to a sharp edge this may well not be the case, a sharp edge on a rock face would likely have a rough surface, and possibly varying effective radius. These irregularities could lead to an even greater reduction in the strength of the rope.

5.3 Pre-Load Testing

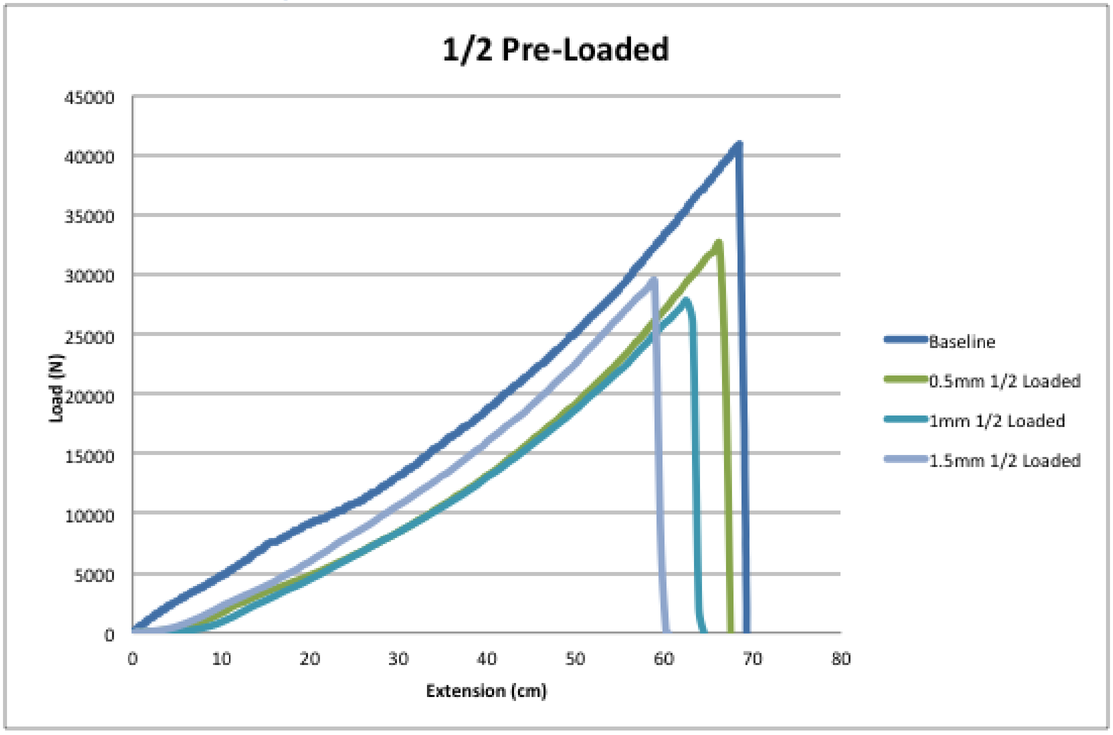

Figure 6 – Load extensions curves of ropes pre-loaded to 50% of their breaking load in respective configurations, then tested to destruction in double rope configuration

In order to establish the nature of the damage caused by loading the rope over a sharp edge some samples were pre-loaded to a predetermined proportion of their breaking load in that configuration. These samples were then tested to destruction in the double rope baseline configuration- running over an eyebolt of radius 5mm.

Figure 7 shows the load paths for samples that were pre-loaded to 50% of their breaking load over their respective edges, and then tested to destruction in a double rope configuration. Also shown is the initial double rope baseline load path for comparison. The pre-loading of these samples has caused their strength over the 5mm edge to decrease by around 25%. There appears to be some interaction between the damaged section of rope and the eyebolt involved in this reduction of maximal load.

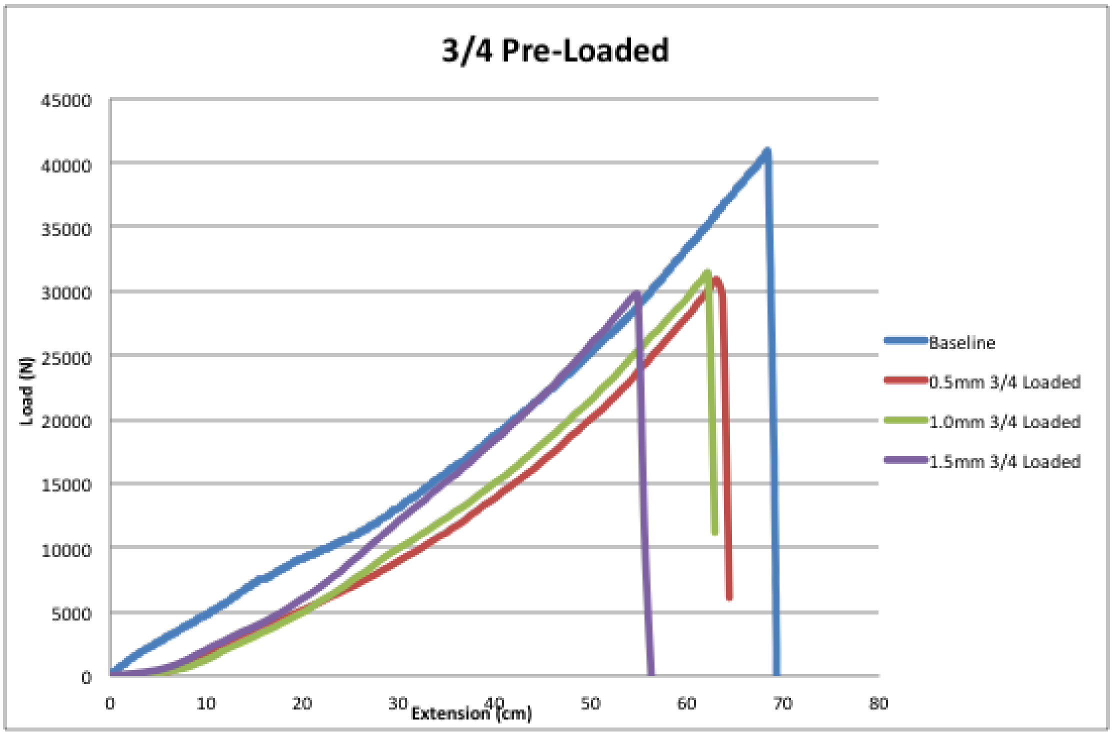

Figure 7 – Load extension curves of ropes pre-loaded to 75% of their respective breaking load in respective configurations, then tested to destruction in double rope configuration.

Figure 8 shows the load paths of samples that were pre-loaded to 75% of their breaking load over the respective edges, and then tested to destruction in a double rope configuration. It is interesting to compare the results obtained from the 50% pre-load and the 75% pre-load- and specifically to note that they are very similar. Both levels of pre-load lead to a breaking load around 30kN, however as can be seen from figures 7 and 8 increasing the pre-load force leads to a more consistent result across the different edges. It can be seen that as the radius of the edge (and so the magnitude of applied pre-load) increases, the steepness of the curve – stiffness of the sample- appears to increase gradually. As was apparent from figure 7 the exposure of the damaged section of rope to the eyebolt is thought to contribute to the reduction in breaking load.

Three samples were then preloaded over the edges, and a fourth over the eyebolt used to provide a 5mm radius “edge” baseline. These ropes were loaded to 75% of their respective breaking load in the relevant configuration. After preloading they were tested to destruction in the single rope configuration.

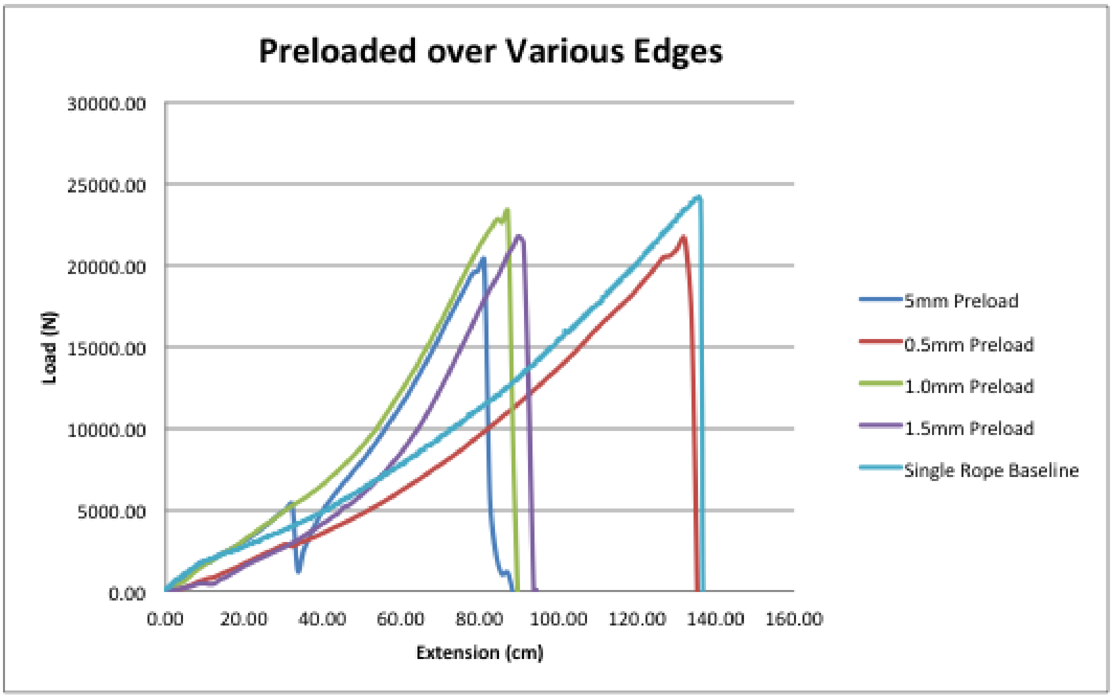

Figure 9 – Load extension curves of samples pre-loaded to 75% of their respective breaking loads, then tested to destruction in single rope configuration

It can be seen from figure 9 that all except the 0.5mm sample exhibited significantly increased stiffness when compared to a baseline (non-preloaded) single rope test. This increased stiffness seems to be around double the initial property of the rope. All the samples experienced a small reduction in ultimate breaking load, however this effect was smaller than when the equivalent destructive testing was performed in the double rope position (where edge damage was liable to be exposed to the surface of the eye bolt).

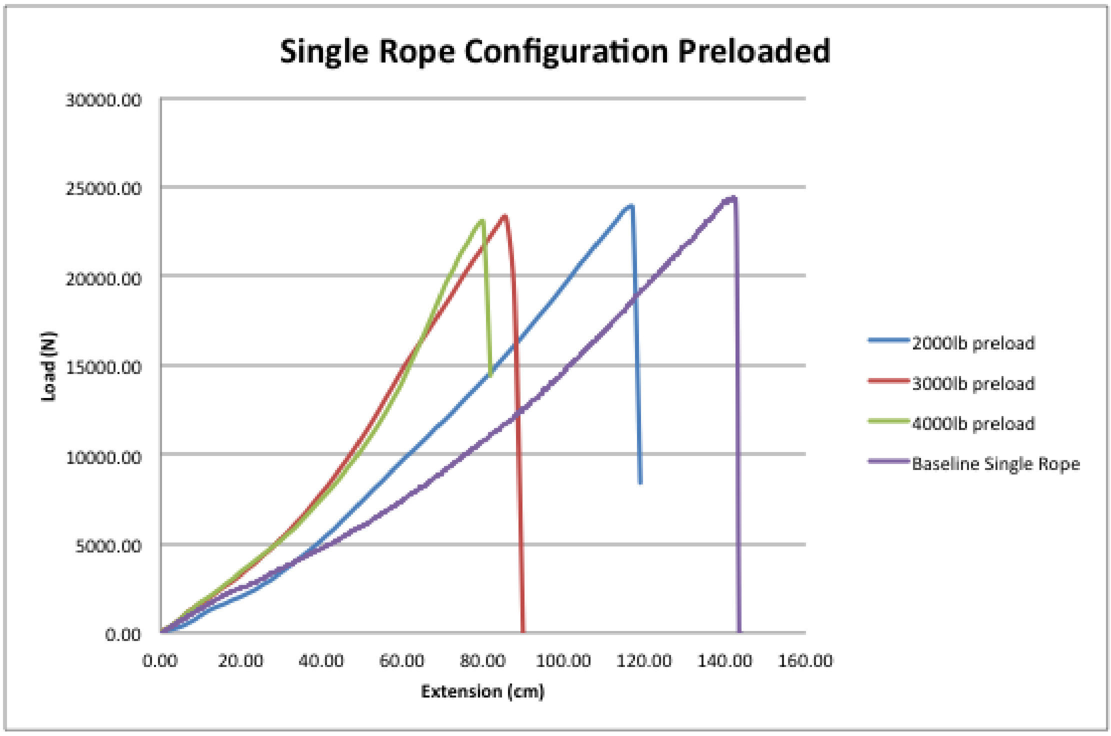

Figure 8 – Load extension curves of ropes pre-loaded to varying levels in single rope configuration, then tested to destruction in single rope configuration.

In order to further examine the cause of the increasing stiffness three samples were pre-loaded in the single rope configuration and then tested to destruction. The corresponding load paths are shown in figure 10. It is evident that an increase in stiffness is present, with an increasing magnitude of pre-load appearing to correspond to a higher stiffness in future testing. However it seems that the rope reaches a maximal stiffness of around double its initial stiffness once the pre-load reaches a certain value. This is also visible in figure 9

It appears that pre-loading a rope over an edge leads to a small decrease in its ultimate strength. This reduction is greatest, as would be expected, when the damaged area is exposed to loading directly (for example the eyebolt used in the testing). When this area of damage is not directly contacting other material it does not appear that pre-loading over an edge leads to a particularly significant loss of strength in the rope.

Any form of pre-loading, over an edge or otherwise, leads to an increase in stiffness. This increase is proportional to the magnitude of pre-load applied to the sample until the effect appears to level off. It is apparent that once that pre-load exceeds a certain value the rope reaches a point of maximum stiffness-where it will extend around half as far for the same load as it would have done before pre-loading. From the testing performed it appears this critical value of pre-load is around 8kN. However in order to establish this fully further testing would be required.

5.4 Rest Time Comparison

A further test was carried out to establish whether these changes in behaviour were due to viscous effects within the material or whether the changes were more permanent. Two samples were pre-loaded in the baseline double rope configuration and allowed to rest for 20 minutes and 20 hours respectively. These samples were then tested to destruction in the same configuration.

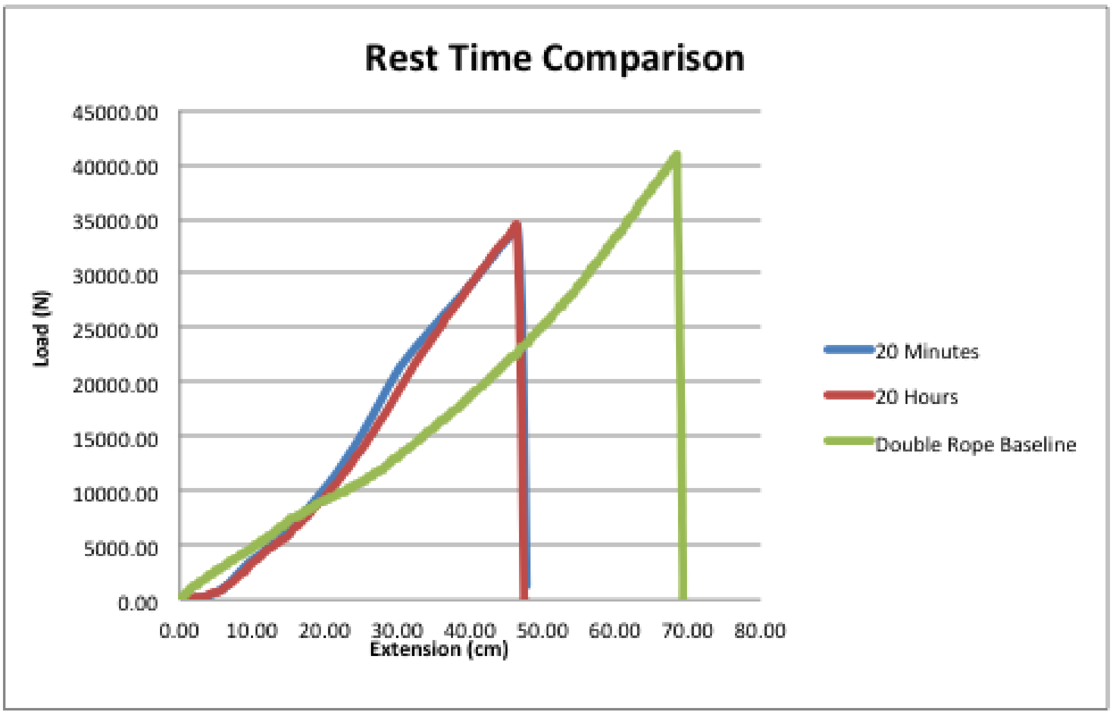

Figure 9 – Load extension curves of two pre-loaded samples, left to rest for 20 minutes and 20 hours

Figure 11 shows the load paths of the two pre-loaded samples and the baseline double rope test for reference. It can clearly be seen that the length of rest time has little or no effect on the stiffness and breaking load of the sample. This result suggests that the change in the rope behaviour is due to a permanent change in the material.

6. Conclusions and Discussion

The ultimate strength of a polymer is dependent on the secondary bonds between the chain molecules, and it is the breaking of these bonds that eventually leads to fracture. The stiffening of climbing rope under pre-loading appears to be evidence of the alignment of the polymer chains within the rope. This follows from the results shown in figures 9 and 10 – where it can be seen that as the magnitude of load applied during pre-load increases, the stiffness of the rope also increases. As a higher force is applied to the rope more of the fibres will become aligned and thus lose their potential to stretch during loading.

From the results it is clear that a climbing rope loaded over a sharp edge will exhibit a significantly reduced breaking load, with decreasing radius leading to decreasing breaking load as tabulated below.

6.1 Breaking Loads over Edges

Edge Radius (mm)	Breaking Load (kN)	Percentage of Baseline Strength
~5 (Baseline)	40.9	n/a
1.5	13.5	33%
1.0	10.5	26%
0.5	5.0	12%

The effect of pre-loading a rope sample over an edge was also investigated. Where the rope was loaded over an edge and the damaged part exposed to the eyebolt for destructive testing in the double rope configuration a reduction in maximum load was seen. However when the edge damage was not exposed to the eyebolt (in single configuration testing) this reduction in strength was not as large. It appears that pre-loading over edges of varying radius does not have a significant impact on the rope's performance where it is not exposed to an edge again. However where the rope has been damaged by a sharp edge it exhibits a lower breaking strength when this damaged portion is exposed to any edge, which need not be especially sharp.

6.2 75% Pre-loaded Rope Breaking Loads

Edge Radius (mm)	Beaking Load Double Rope (kN)	Percentage of Double Rope Baseline (40.9kN)	Breaking Load Single Rope (kN)	Percentage of Single Rope Baseline (24.2kN)
1.5	29.7	73%	21.7	90%
1.0	31.3	77%	23.3	96%
0.5	30.8	75%	21.6	90%

Pre-loading climbing rope increases its stiffness, and where the ropes were loaded to above 8kN they exhibited a roughly doubled stiffness. Below 8kN smaller increases in stiffness were seen, and above 8kN it appeared that the rope did not become stiffer. This increase in stiffness is thought to be due to plastic deformation in the material microstructure as the polymer chains become permanently aligned and stretched.

6.3 Further Research Possibilities

The testing performed established an understanding of the behaviour of climbing ropes loaded in a quasi-static situation. Further work on investigating the behaviour in a dynamic, drop test simulation would provide data more relevant to climbing itself and thus of more use to manufacturers and regulatory bodies such as the UIAA. It would also be interesting to further investigate the behaviour of pre-loaded ropes with more tests performed at closer spaced intervals of proportion of breaking load. For example to pre-load samples to 50%, 60%, 70% etc and then test them to destruction. From this it would hopefully be possible to establish at what point the fibres are well aligned in the material by examining when the rope appears to reach a maximal stiffness. Beyond this level of pre-loading one would expect a reduction in ultimate strength as some of the bonds between the polymer chains would presumably have been broken. An in depth study into this phenomena would likely yield interesting results.

7. Acknowledgements

The author would like to extend his sincere thanks to the following people, as without their various contributions this project would not have been possible. Dr Andrew McLaren for his guidance and supervision throughout the duration of this project. Mr Andrew Crockett for his assistance in the testing of rope samples. Mr Chris Cameron and Mr Fuad Warsame for consultation and construction of the testing rig respectively. Also Mr Jim Docherty, manager of the Mechanical Engineering stores for use of his facilities and equipment.

8. Bibliography

1. *Number of Rope Failures amongst German and Austrian Mountaineers and Climbers since 1968.* **Schubert, Pit.** Turin : s.n., 2002. Turin Rope Conference. p. 1.

2. **UIAA.** UIAA 108 Suspended. *UIAA.* [Online] July 2004. http://www.theuiaa.org/upload_area/files/1/Important_notice-_UIAA_Safety_Standard_108_suspended(0)(1).pdf.

3. *Sharp Edge Testing of Mountaineering Ropes.* **Oliver Henkel, Mammut AG.** Turin : s.n., 2002.

4. *Sharp Edge Testing, Status and Prospects.* **Zanatoni, Carlo.** Turin : s.n., 2002.

5. *Polyamide 6. The Right Material for Ropes: Its Production and Technical Characteristics.* **Ernst, Elmar.** Turin : Rhodia Industrial Yarns, 2002. Turin Rope Conference.

6. **Alger, M. S.** *Polymer Science Dictionary.* London and New York : Elsevier Science Publishers LTD, 1989.

7. *Fracture of Nylon Fibres.* **Jacobson, Dr Karin.** Turin : s.n., 2002. Turin Rope Conference.

8. **Callister, William D.** *Materials Science and Engineering.* 7th Edition. s.l. : John Wiley and Sons Inc., 2007. pp. 535-538.