Fatigue Wear of Passive Climbing Protection

by

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Summary

This project is concerned with the impact of fatigue and cumulative damage on nut anchors, a form of protective device for rock climbers. Nut anchors typically consist of two parts: an aluminium wedge and a threaded steel cable. These are placed in rock features, in such a way as to arrest a climber in the event of a fall. Anchors are tested according to regulating standards with single-pull-to-failure tensile loads. These loads seek to mimic the effect of a dynamic fall by a roped climber and establish the maximum force withstandable by a particular type of anchor. However, these tests fail to represent consistent use such as from many successive falls.

Consequently, the aim of this report was to investigate the likely behaviour of such anchors under continued use to allow for estimation of their longevity. This was done with combined investigation into the phenomenon of metal fatigue and the failure modes of passive protection. Further investigation was also made into accumulated damage theory to provide a basis for numerical stress and fatigue analyses. These analyses took the form of finite element analysis and simulated fatigue cycling, all of which were produced with SolidWorks simulation studies on a 3D model of a nut anchor.

The results of these analyses were to provide the magnitudes of stresses corresponding to climbing falls of varying severity. With this stress data and quantitative estimations of the average fall frequency of a climber, the longevity of climbing protection was found both in terms of load cycles and usage lifetime estimates. It was found that, when placed with their largest faces fixed in a constriction, anchors would last upwards of a million cycles up to their rated strengths. However, when placed in a perpendicular orientation, they were found to last as little as 7000 cycles, representing several orders of magnitude in difference.

However, these results were derived from a swage less model of a nut. This was used due to conflicting boundary conditions encountered when attempting to simulate loads on a 3D swaged model. The results therefore represent a theoretical upper limit to the longevity of nut anchors. Consequently, it is necessary for a practical test to be conducted to find the real limits of use of the same anchor. This should, as closely as possible, resemble the fatigue simulations to allow a safety factor to be established between the virtual and real fatigue testing methods. The resulting test would therefore adopt a methodology derived from constant-stress testing, as only constant amplitude loads were applied throughout the simulations conducted in this report. A corresponding safety factor could then allow for further scaled testing of anchors.

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1 Introduction

1.1 Background

This project is concerned with the equipment used to arrest falls in traditionally protected rock climbing and mountaineering. Rock climbing and mountaineering constitute a popular recreational activity with approximately 25 million regular participants worldwide (IFSC, 2016). Traditional climbing refers to roped climbing where there are no pre-existing anchors within the rock face to be attempted. As the lead climber ascends the cliff, en-route they will place removable anchors in an ad hoc fashion. These anchors can consist of a variety of devices which make use of different features in naturally occurring rock. The climber's partner is referred to as the second or belayer. They will safeguard the leader by braking the rope in the event of a fall, in which case, the leader will be suspended by the most recently placed anchor. Consequently, a force is experienced by the climber, rope and the anchor. This project will focus on the protective devices known as 'nut' anchors, with the aim of estimating their longevity under the loading conditions that correspond to their typical use.

1.2 Definitions

Traditional Climbing – most commonly known as 'trad' climbing, as explained above. Contrasts with sport climbing whereby pre-existing bolted anchors are used to protect a fall.

Protection, Anchor, Runner or Gear – terms all collectively referring to the variety of devices used to safeguard a fall in roped rock climbing. Protection can be either active or passive, consisting of moving parts or none, respectively.

Nut, Wire or Chock – passive protective devices commonly made from aluminium or brass with a wedge shape. When properly placed in a tapering crack, these can hold falls due to their geometry and the presence of a mechanical constriction.

Belayer and Lead Climber/Leader – terms referring to the two people that constitute a climbing pair. The belayer remains at a fixed position and pays out rope to allow the leader to move upwards, they are responsible for braking the rope to arrest the fall of a leader, provided there is protection placed to allow for this.

Connector or carabiner – metal shackle components which provide the critical link between protection, the climber and the rope. They have spring loaded gates to allow for reversible capturing of the rope. Used in fall protection, anchoring and belaying.

1.3 Rope theory

To consider the forces on climbing anchors, an understanding of rope energy absorption is necessary. In a lead climbing fall, the associated forces are proportional to the elongation of the climbing rope. Climbing ropes are dynamic and it is their elongation that is responsible for most of the dissipation of energy arising from impact. The remaining energy of impact is then concentrated into the forces applied to the anchor and climber. A quantitative estimation can be made with the following quadratic rope model seen in **Equation (1)** (Goldstone, 2006):

(1) $$T = mg + \sqrt{(mg)^2 + 2kmg\left(\frac{h}{L}\right)}$$ **(2)** $$F = (5/3)T$$

Where T *(kN)* = tension in the rope, m *(kg)* = mass of lead climber, k *(kN)* = rope modulus, g = acceleration due to gravity ≈ $9.8ms^{-2}$. Values h and L correspond to those outlined in **Figure 1** Below, F *(kN)* = Force incident on highest anchor. The further relationship seen in **Equation (2)** relates the resulting rope tension to the impact force on the highest anchor.

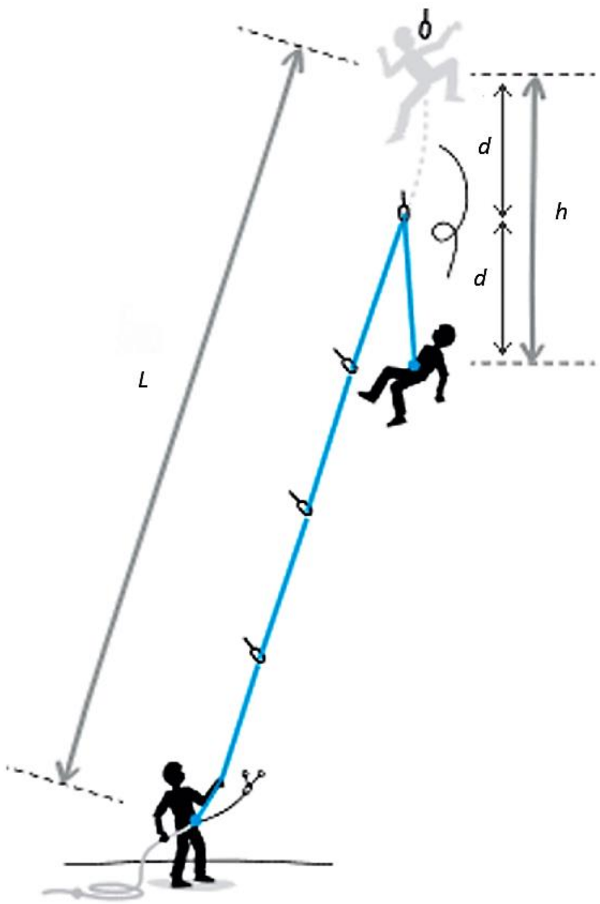


Figure 1: Lead fall taken by a roped climber with factors relevant to analysis of forces **(Petzl Group, 2018)**

$h = 2d$, height of fall taken by lead climber

d = height of climber above highest anchor at instant of fall

L = total length of rope between belayer and leader

Considering the above equations, any climbing fall can be analysed to provide an estimated anchor impact force. The stresses on the gear can then be calculated allowing for analysis of damage, fatigue and the longevity of the involved hardware. Such analysis will form the aim and premise of this project.

*The lengths above are used to calculate the fall factor ratio. Therefore, units are redundant, provided there is consistency in the base units used for the parameters h, d, L and for the eventual calculation of the fall factor.

1.4 Research Question

This project will seek to find the answer to the following research problem:

How should a reliability test be composed to establish the limits of use of metal passive climbing protection?

1.5 Project Aim

The aim of this project is to design a reliability test that would establish the limits of fatigue wear on nut anchors. This project would seek to investigate the limits of use of these anchors with varying frequencies of use and magnitude of force applied. This will be achieved with the use of Finite Element Analysis (FEA) and Fatigue Analysis software. With the results obtained, a practical laboratory test will be designed on an appropriately chosen reliability test methodology to allow real safe limits of use to be established.

1.6 Project Objectives

To achieve this aim, the following objectives will be used to establish progress of the project:

1. Investigate failure modes arising from the combination of impact damage and fatigue with regards to the continued use of passive climbing protection.
2. Conduct FEA using 3D models of current protection with further use of software for fatigue analysis and degradation testing.
3. Given both the findings of the failure investigation and software results, design a practical laboratory test to establish real limits of use of hardware with appropriate reliability test methodology.

1.7 Project Scope

To provide realistic scope for this project, the following considerations have been made:

1. Investigation is made only of passive climbing protection and specifically metal chock anchors. Active protection such as spring-loaded camming devices are ignored on the basis that such devices consist of complex mechanisms with too many possible failure modes and constituent components with which to conduct relevant testing. Omission is also made of textile components and connectors (carabiners) to allow for focused stress analysis of the chosen hardware.
2. The project will consider only the mechanical effects of impact damage, wear and cyclical fatigue on the chosen hardware. This is also to allow for focused study of

mechanical stresses only, as concerned with dynamic and static roped loads in rock climbing.

3. Practical laboratory testing itself will not occur as tensile testing requires specialist vice grips that would be tailor-made for nut anchors. More critically, fatigue cycling of mechanical components that would yield meaningful and conclusive data would require upwards of millions of cycles. The estimated time and material costs therefore exceed those deemed reasonable for the ES327 project. Software simulations consisting of FEA and fatigue analysis will take place instead to allow for virtual degradation and estimation of the longevity of hardware.

1.8 Project Justification

The premise of this project is that, though largely constructed from aluminium, which has known susceptibility to fatigue (Srirangam, 2017), there is no standard reliability or fatigue test for the longevity of climbing protection. Most climbing hardware is made from aluminium as it provides a compromise between strength and low weight, the latter being a critical element of equipment produced for the sport.

British standards that exist for passive climbing protection under BS EN 12270 detail only one testing procedure. This consists of a single tensile load test that establishes the rated breaking strength for any given piece of climbing protection (BSI, 2013). In most climbing use, protection is reused throughout the lifetime of a climber with variable loads that do not correspond to the extreme case scenario presented by standard tests. According to the technical committee of the British Mountaineering Council (BMC), average climbing falls reach peak forces of between 4-7kN whereas standard passive protection is typically rated to between 10-12kN. Hence failure of climbing protection is more likely to occur through cumulative damage and fatigue wear rather than in a single instance of loading.

An investigation is thus needed to ascertain the fatigue limits of passive protection. This will require examination of currently available hardware and their constituent materials. Consideration must then be made of likely stress cycles and loading to allow for software simulation. Lastly, practical laboratory testing should take place to establish the real limits of wear on passive climbing protection. An appropriate reliability test methodology will be selected, based on the findings of the software simulation, by which the practical testing will occur.

1.8.1 Value of the project to the user, business and society:

Currently, protection is recommended for replacement upon suspect wear and visible fraying or damage (Black Diamond, 2015) as such, the criteria for replacement is too vague, and is thus open to misinterpretation by climbers. Moreover, near fatal accidents have occurred due to equipment failures derived from overuse and fatigue wear (BMC Technical Committee, 2009). Successful completion of this project and subsequent conducting of the associated test would allow for estimation of the true longevity of properly used passive protection.

An appropriate safety factor could then be chosen to establish safe recommended limits of use for climbers considering stress cycles typical of the use of such gear in rock climbing. Furthermore, quantitative estimation of impact forces in climbing falls could then be used to relate every instance of a fall to the corresponding stresses on hardware.

A resulting lifespan estimate could then be produced either in cycles (falls) or in terms of a statistical lifetime's worth of climbing. Care should be taken to ensure statistical limits are considered in relation to abnormal use. Ultimately however, this would allow for a quantitative guideline for the longevity of nut anchors. This would be less open to misinterpretation and could be beneficial to climbers and manufacturers of hardware.

If gear was to be methodically treated as such by the wider climbing community due to results from this project, then the likelihood of climbing accidents from gear failure would be reduced. A further benefit may be that, with more thorough knowledge of fatigue failure with regards to nut anchors, manufacturers may be able to further optimise the design of protection.

1.9 Project Structure

The main body of this report will be comprised as follows:

Introduction
- Background, Research Question, Aims and Objectives, Justification

Investigation of Existing Hardware
- Background technical information relating to existing nut anchors, their constituent materials, rated strengths and their certification standards

Investigation into Reliability Testing
- Evaluation of test methodologies and consideration of software tools for the broader reliability testing of mechanical components

Analysis
- FEA and Fatigue analysis simulations

Practical Test Design
- Design of a practical test for nut anchors, with an appropriate methodology chosen with consideration of the simulation results

Conclusions
- Verification of whether project has met intended objectives

Future Work
- Discussion of future practical testing and experimental method

2 Passive Hardware

2.1 Background

Nut anchors are one of the most commonly used forms of protection for rock climbing. They are a versatile piece of equipment that, if used correctly, can hold a falling climber. To do so, nuts are placed in constrictions in cracks. It is important that the crack narrows vertically downwards for their holding power to manifest. A nut is shown to the right in **Figure 2**, having been placed in such a position. A climber would clip their rope, through a carabiner (connector), to the connection point of the nut and be arrested by it, should they fall within a reasonable distance from it. The height of such a fall, the mass of the climber and the length of rope in the system would determine the forces incident on this nut.

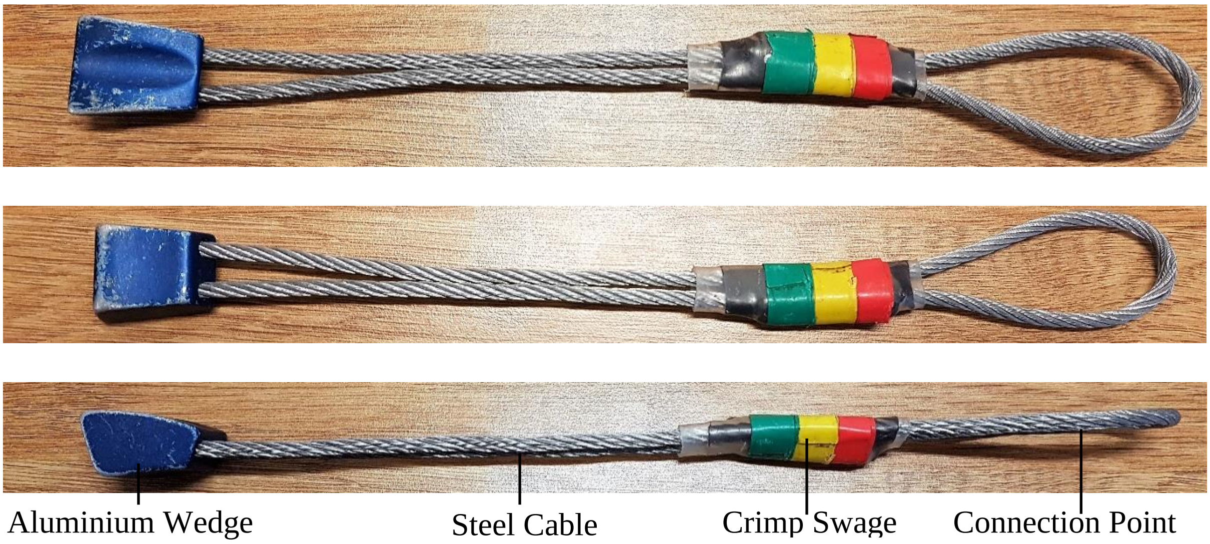
As nuts are largely constructed from aluminium and given the susceptibility of aluminium to metal fatigue (Srirangam, 2017), nuts have been chosen for study in this report. Connectors are also made of aluminium but have not been chosen for study as their fatigue behaviour has been more thoroughly researched (Black Diamond, 2015). The last pieces of the safety chain are the climber's rope and harness. The behaviour of these textile components is not concerned with metal fatigue, so they have been ignored. Appropriate mathematical models **(1.3)** have been implemented to consider the effect of connectors, the rope and harness in calculating the impact forces on nut anchors.

Figure 2 (right): DMM Wallnut rock placement with connector **(Begley, 2016)**

2.2 Mechanical Features

Nuts consist of two components: an aluminium wedge (which may be hollow or solid) and a loop of steel cable which is threaded through the wedge. The wire is threaded through two pairs of holes drilled into the top and bottom surfaces of the wedge. The wire is joined at a swage using the Talurit Ferrule system, this is effectively a tightly crimped swage.

Figures 3a-c (top to bottom): DMM Wallnut size 5; front, rear, side faces



The nut shown is produced by DMM with the wedge constructed from 7075 alloy aluminium. Larger nuts typically have hollow cross-sections to reduce their weight. Larger nuts tend to be of softer alloys due to the larger contact areas involved in a placement. The larger area results in lower shear forces and so, a less stiff material is required. DMM wedge sizes 7-11 consist of 6082 alloy (DMM, 2016). Widths of the nut wedge range from 6.7/14.3mm (size 1) to 33.1/37.4mm (size 11), the dual dimensions result from the two different placement orientations with either the front/rear faces or the smaller side faces in contact with the rock.

Table 1: Mechanical Properties of 7075 and 6082 Aluminium Alloys (Aalco , 2017)

	Al 7075-T6	Al 6082-T6
Brinell Hardness	150	93.0
Young’s Modulus/GPa	71.7	69.0
Elongation at Break/%	11.0	10.0
Fatigue Strength/MPa	159	95.0
Poisson’s Ratio	0.33	0.33
Shear Modulus/GPa	26.9	26.0
Shear Strength/MPa	331	220
Ultimate Tensile Strength/MPa	572	310
Yield Tensile Strength/MPa	503	260

Shown previously are the mechanical properties of the alloys used in DMM nut anchors. The most relevant property to reliability testing is the fatigue strength and this will be important when considering the results of the FEA and fatigue simulations. It is worth noting that the involved alloys are treated beyond normal fabrication. The treatment applied to DMM nuts consists of solution heat treating and subsequent artificial ageing, resulting in the T6 temper designation for their alloys. The properties shown reflect this treatment.

2.3 Gear Impact Forces

The elongation of the rope and the mass of the climber are the determining factors for the impact force on a nut anchor. With the relations outlined previously in equations **(1)** and **(2)**, the direct relationship between fall factor and the impact force on the nut can be observed for a given mass and rope modulus.

Table 2 below displays the resulting fall forces considering the industry standard assumptions of an 80kg climber and rope modulus of 24 (UIAA, 2017):

Fall Factor	Impact Force/kN
0	0
0.25	6.58
0.50	8.65
0.75	10.25
1.00	11.61
1.25	12.80
1.50	13.89
1.75	14.89
2.00	15.82

Critically, impact forces can exceed the ratings of even the hardiest protection (12-14kN), even short of the worst-case scenario of a factor 2 fall. It is worth noting however, that the real-life behaviour of dynamic ropes under load is not entirely true to the chosen model (Goldstone, 2006). Additionally, factors such as the belayer's braking action and slippage in the leader's knot, work to reduce the total forces. To accurately determine the actual effect of such forces on the gear, focused stress analysis is necessary and will be conducted in the simulation phase of this project.

2.4 Failure Mechanisms and Likely Stress Concentrations

Inspection of the geometry of the nuts suggests that the greatest stress concentrations would occur within the wire thread points of the wedge, as they have the smallest area. Failure might also occur at the cable due to the presence of the crimp swage and small diameter of the wire (Minguez, 2006). A challenge is presented here in that these two differing failure mechanisms occur within two different materials. This project's premise is derived from the fatigue susceptibility of aluminium, so only failure of the wedge is considered. If it was found that the only common failure mechanism was one that occurred within the steel cable, this premise would be undermined as steel has a defined fatigue limit. Despite this, an alternative investigation could be found to concentrate on instances of low cycle fatigue within the steel cable, as this is a known concern in the study of engineering failures (Qingyuan, 2011).

3 Reliability Testing

3.1 Introduction

Reliability testing broadly refers to any test performed on a product, the results of which can be used to improve its reliability - the ability to perform its function, without failure, for a given period. There are two broad categories of test that can be used to evaluate reliability: those that simulate the expected operating conditions of a product and those that stimulate failure instead (Thermotron, 1998).

The latter aims to subject a product to conditions harsher than those in normal operation. These harsh conditions may result from any combination of higher applied stresses or exaggerated environmental effects such as corrosion and wear. This is done to reduce the time and material costs required for testing under normal operating conditions, particularly with long-lasting components.

Simulation tests differ from stimulation ones by attempting to mimic conditions under normal use. They attempt to accelerate failure under a known mechanism by exposing a product to its expected stresses yet at a much faster rate or duty cycle. A variety of test methods from both these categories can be used on products, but the data produced is generally extrapolated back to the expected performance under normal conditions (Elsayed, 2012). Statistical methods can then be used to establish a predicted product lifespan.

3.2 Reliability Test Methodologies

There are many forms of practical reliability test, of which only a few are best suited to mechanical components. Establishing the longevity of climbing protection, with regards to fatigue, will place further restrictions on what constitutes a suitable test. This section will aim to investigate the different reliability tests and select the most appropriate one for the study of fatigue in nut anchors.

3.2.1 Accelerated life testing (ALT)

A broad variety of testing methods which accelerate the degradation of a product through either an accelerated duty cycle or periodic application of higher stresses. This aims to reduce the product life and hence testing period yet with the provision for analysis to extrapolate an expected lifespan under the stresses experienced under normal use.

3.2.1.1 Constant stress testing

When tested, the component is exposed to stresses of constant amplitude. While constant stress testing is suitable for components that typically encounter only constant stress levels, nut anchors are almost always exposed to varying stresses. It is still possible to use a constant stress test on components that encounter varying stresses however (Nelson, 1990). The amplitude chosen must be greater than the upper bounds of typical use. A rough representation can be obtained of likely real-life performance, it is still statistically inaccurate and difficult to accurately predict product life of varying stress components with a constant stress test.

3.2.1.2 Step-stress testing

The component is initially subjected to stress at a constant level for a specific period. If failure does not occur, higher stresses are applied incrementally until failure, with the time spent at each stress level recorded. A pattern is observed after many specimens where the relationship between stress level and period can be determined. This correlates to the SN characteristics displayed by components undergoing fatigue wear and so, is promising for the purposes of this project (Lee, et al., 2005). A problem with this method is that it assumes proportional behaviour under overstress conditions compared to those of normal use, allowing for linear extrapolation. This is contradicted by the fact that materials under overstress conditions are typically operating in the non-linear region of their stress-strain characteristics.

3.2.1.3 Highly accelerated life testing (HALT)

A method of incremental stress increase that proactively seeks to provoke as many failure modes as possible within the product being tested. This is done through a combination of harsh environmental conditions and the application of stresses beyond operational limits. This method is typically confined to the electrical domain (Bertsche, 2008) due to the more stochastic nature of operating conditions and variability of failure modes from varying environmental conditions in electrical circuits e.g. power surges. The greatest limitation of HALT is that it does not allow for statistical analysis of the reliability of a product. It is therefore unlikely to be suitable as such statistical analysis is fundamental to the ability to predict component lifespans, as required under the premise of this project.

3.2.1.4 Accelerated degradation testing (ADT)

ADT is the only method to account for the effect of wear on a component and its contribution to failure. The wear of the component is measured for a given period and extrapolated to a finite point at which failure is deemed to occur. The relationship of interest is the rate of degradation of the product's performance with time. This is particularly relevant to the concept of metal fatigue and includes potential for the consideration of abrasive wear in the use of nut anchors. An issue arises from the potential inaccuracy of extrapolation given the variability of material microstructures within fatigue testing. This applies to all testing methods and is addressed in section **3.5**, concerned with the particulars of metal fatigue.

Table 3: Comparison of testing methodologies

Test Method	Appropriate for Fatigue Analysis?	Appropriate for Mechanical Components?	Representative of actual climbing use?	Allows Statistical analysis?
Constant stress	~	✓	x	✓
Step-stress	✓	✓	~	✓
HALT	x	x	x	x
ADT	✓	✓	✓	✓
CAE	✓	✓	~	✓

3.2.2 Discussion

Considering **Table 3** above, some methods are clearly more appropriate than others. This project seeks to predict the lifespan of climbing protection and so statistical analysis is necessary to do this. Consequently, HALT is an unsuitable test methodology as its primary aim is to establish failure mechanisms under many simultaneous stresses and environments. This makes it impossible to extrapolate data as there are too many variables involved. Similarly, constant stress testing is unlikely to allow for accurate extrapolation to the typical use of nut anchors because they typically encounter immensely variable stresses. The methods of ADT and step-stress testing may be the most likely candidates as their testing methodologies correlate to the phenomenon of metal fatigue, which this project is oriented towards.

For definitive selection of a testing methodology, a clear understanding of the stresses incident on nut anchors is necessary. The following sections attempt to provide preliminary stress analyses as a build up to FEA simulations along with virtual fatigue simulations. With the results of these in mind, a practical reliability test can be designed with appropriate selection of a method from the above.

3.3 The use of software simulations for reliability testing

Though typically incorporated into the design phase of a product, computer aided design or engineering (CAD, CAE) can be used for reliability testing of a component. This typically requires the use of finite-element stress analysis (FEA) along with further software to simulate fatigue cycling. Software analysis can provide a quick and convenient insight into the likely fatigue characteristics of a mechanical component when time or material constraints limit the feasibility of practical testing (such as in this project). There are many limitations of the use of software simulation however, these are covered in section (**3.4**) which provides an evaluation of its use within the context of this project. Further study is also necessary to establish the methodologies and statistical methods by which the software simulations may occur.

3.4 Evaluation of FEA and Fatigue Analysis Software

As part of the simulation phase of this project, it is intended that SolidWorks fatigue analysis software will be used. SolidWorks fatigue analysis can operate by instances of either variable amplitude or constant amplitude loading (Solid Solutions, 2010). The unpredictable nature of recreational rock climbing presents the problem of loading that varies in amplitude, though this is typically much harder to analyse statistically (Xiong & Shenoi, 2011). Further consideration of the nature of such loading is made in section **(3.8)**. There are many limitations of the use of finite element methods as a means of virtual testing, these are detailed below:

1. SolidWorks FEA and fatigue analysis does not consider:

    a) The continual effect of abrasive wear throughout the cycling of the component. This is important with regards to the use of nut anchors as finding a secure placement often requires the climber to tug the nut into an appropriate constriction repeatedly. Removal of the nut afterwards often requires aggressive tugs in the opposite direction. Such tugs are applied as arm length loads by the climbers – they therefore represent a very small proportion of the forces involved in a dynamic fall. Both the placement and removal processes involve abrasive wear against the area of rock being used. This leads to loss of material and hence some loss of strength. This process occurs with every cycle and so might influence the fatigue life but cannot be accounted for with the chosen software. It can be noted however that this wear is typically uniform in nature and occurs on the large faces of the wedge and so is unlikely to result in stress raisers or drastically accelerate failure.

b) Similarly, to the above, when nuts are removed they are typically held at the opposite end to the wedge and yanked upwards. This is a widespread procedure for their removal, yet it can inflict bending loads on the steel cable. As climbing gear is designed to take almost purely tensile loads, this may disproportionately accelerate failure. SolidWorks fatigue analysis cannot simulate the cycling of multiple types of load (i.e. bending as well as the normal tensile loads due to falls). This form of loading is therefore ignored, as the dynamic tensile loads are of greater magnitude and are more in line with the project aim.

c) The presence of dislocations and defects, which are inherent in any real component made from a real material. This results in a component of reduced strength before any of the effects of wear are considered.

2. The software simulations make use of meshing to compute the geometry of the model and resolve the incident forces and their resulting stresses. A mesh must be finite and so there is intrinsic uncertainty (the magnitude of which is dependent on the mesh size) in the simulation results.

3. Simulations are unlikely to provide the variety of unexpected failure modes presented by real life testing.

*It is important to note that due to the high thermal conductivity of metals, a high frequency of fatigue cycling does not raise the energy at which further stresses occur (O'Connor & Kleyner, 2012). The implications of this is that the frequency of loading has negligible effect on the accumulated damage of the product. The fatigue life can then be deemed a function solely of the number of cycles and magnitude of stress applied, and so, loading frequency can be ignored (Nelson, 1990).

3.5 Fatigue and S/N cycles

3.5.1 Introduction

Fatigue is a process by which materials degrade under repeated cyclic loading. This relates to the gradual propagation of cracks in the material microstructure. Materials susceptible to fatigue may fail at loads much lower than their yield strengths given enough stress cycles. An SN plot or Wöhler curve can characterise the fatigue response of any material. These relate different magnitudes of stress to the number of cycles needed to cause failure at that stress. A material may have a stress limit below which any number of cycles cannot cause failure, this is known as the fatigue limit. Of the common metallic engineering materials, ferrous metals are known to have finite fatigue limits whereas aluminium does not (Srirangam, 2017). Therefore, stresses of low amplitude, if applied over a large number of cycles can cause failure.

3.5.2 Fatigue as applied to nut anchors

The project is concerned with the phenomenon of metal fatigue as applied to the cyclical use of nut anchors. This section seeks to identify the susceptibility of nut anchors to fatigue, through the comparison of basic stress analyses to known fatigue data.

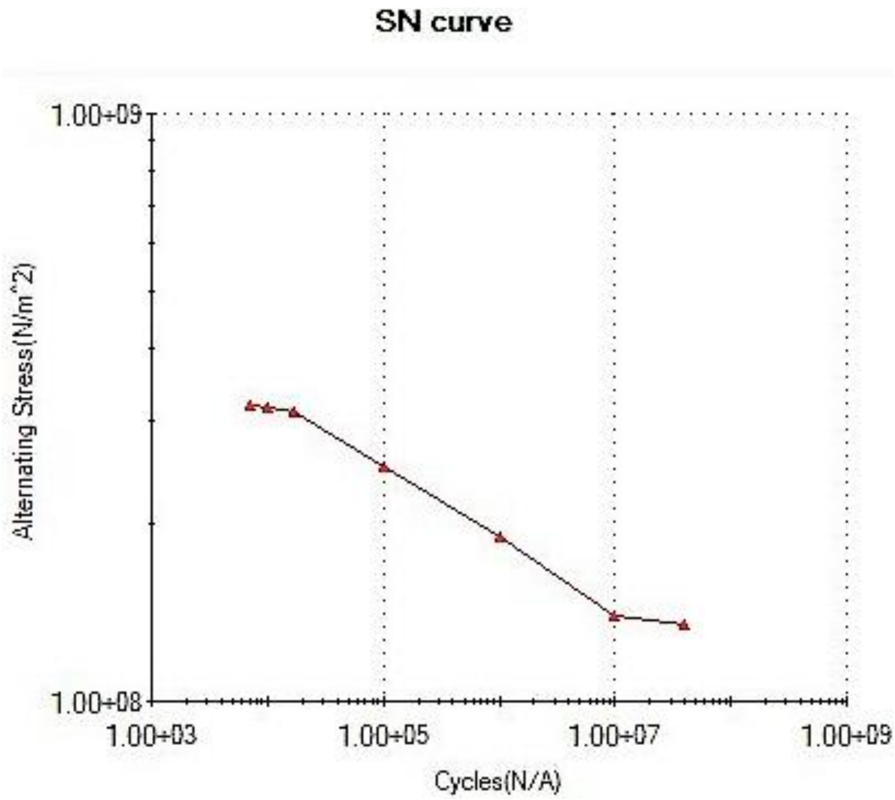


Figure 4: S/ N curve for 7075 - T6 aluminium **(Granta Design, 2017)**

Figure 4 shown represents the SN characteristics of the 7075-alloy used in small to midrange nuts (DMM, 2016). There is an evident linear trend in the fatigue characteristic displayed, however the levelling off at the rightmost section of the curve implies the existence of a fatigue limit. This is somewhat in contradiction to the premise of the project yet is likely due to the high-strength nature of 7075 - T6 aluminium alloys (Aalco , 2017).

The smallest loads, of the order 100MPa require about 100 million cycles to failure whereas the highest loads of ~ 500MPa require as few as 100 cycles for failure to occur. Small static loads are applied to anchors in many aspects of climbing, beyond lead falls, and so further consideration will be made of this. These small loads occur more often in climbing and so will be relevant to the right-hand side of the S/N curve, under low stress - high cycle fatigue. The larger forces involved in lead falls will involve the left-hand side, under low cycle fatigue, where the involved stresses are much closer to the failure strength of the material.

Considering **Figure 5** below, a similar semi-linear trend is evident within galvanised steel. However, there are important differences. The yield strength at the extreme left of the curve is shifted upwards from the Al curve suggesting that catastrophic failure from one-off instances of loading is more likely to occur within the wedge than the cable. Conversely, the cross-sectional area of the cable is much smaller than any part of the wedge, so the involved stresses will be higher. Further analysis is necessary to determine the extent to which the cable is affected by loading and how this compares to the wedge component.

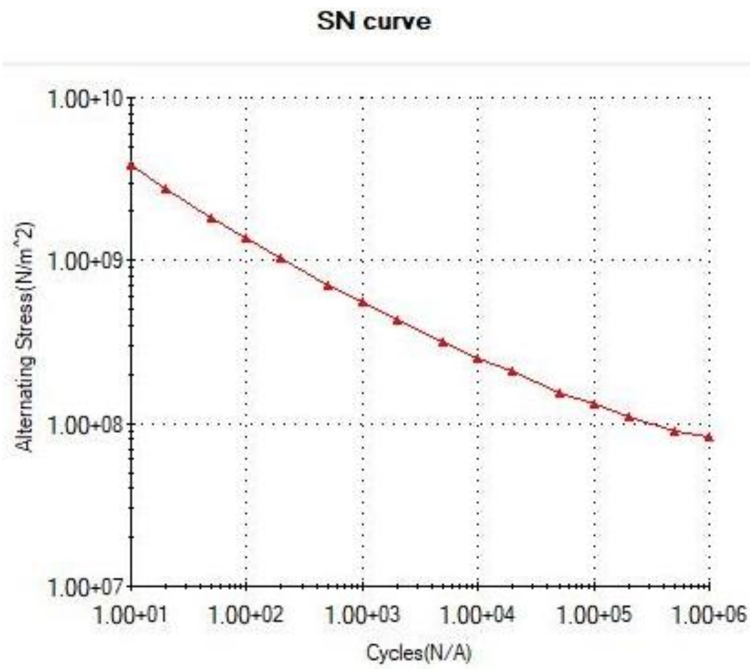


Figure 5: S/N curve for galvanised steel **(Granta Design, 2017)**

Importantly, the SN characteristics displayed only consider each respective component according to their constituent material. The use of SolidWorks FEA and Fatigue Analysis aims to establish the compound fatigue characteristics of a complete nut anchor. This will be done with the combination of focused stress analysis under set external loads and subsequent virtual fatigue cycling of the same load. The process may be repeated for different load magnitudes to correlate to the stress – cycle characteristics presented by an S/N curve. The result of this process, when combined with cumulative damage theory (**3.7)**, will be to provide quantitative lifespan estimates for nut anchors, as aspired to by the premise of this project.

3.6 Preliminary Stress Analysis

Considering the known S/N characteristics of aluminium, a preliminary analysis of the likely stresses incurred in climbing loads can be found. The following calculation is the most basic form of stress analysis and will be followed up by more precise FEA simulations:

$$Stress = \frac{Force}{Area} \qquad \sigma(Pa) = \frac{F(N)}{A(m^2)}$$

*In this instance, the stress is assumed to act solely on the area formed by the bottom wedge face of a DMM walnut size 6 (approximately 15mm x 10mm = $1.5 \times 10^{-4} m^2$)

- This size has been chosen as the mid-point in the DMM range of nuts for rough quantitative analysis of the stresses involved.
- The load has been considered to act through just the aluminium wedge with the steel cable ignored, to relate to the known fatigue characteristics. This is in line with the original premise of the project, focusing on the aluminium component and its fatigue susceptibility. However, the galvanised steel SN curve suggests a similar susceptibility of both the cable and wedge.
- FEA should establish the realistic failure modes of nut anchors in typical use.

Table 4: Fall forces and Corresponding Stresses

Force (N)	Approximate Fall Factor	Stress (MPa)	Proportion of Yield Strength ≈ 530MPa (%)	No° Cycles to Failure
0	0	0	0	∞
800	True Static Load	5.3	1.0	∞
1,600	Static Roped Load	10.7	2.3	∞
2,620	0.125	17.5	3.7	∞
6,580	0.25	43.9	9.3	∞
8,650	0.50	57.7	12.3	$>>10^8$
10,250	0.75	68.3	14.5	$>10^8$
12,000	1.10	80.0	15.1	$>10^8$
14,000	1.50	93.3	19.8	$\sim10^8$

The results above present a rough idea of the stresses involved in climbing falls to varying extents of severity. It is important to note that at 14kN (the largest common rating for any climbing protection), the number of cycles to failure is of the order 10^8. This is incredibly high in relation to the likelihood of people partaking in the corresponding fall parameters, yet alone regularly.

A fall of greater than 10kN impact force may result in internal injuries to the lead climber with a very real potential for permanent back and spine damage (IOTA Climbing, 2016). It is therefore extremely unlikely that a climber in their lifetime would seek to undergo any. This would appear to suggest that fatigue failure is unlikely to occur of nut anchors within one lifetime. The following alternative use patterns may then be considered: 1. Centre or group use of nut anchors whereby multiple individuals use the same gear 2. Successive use of the same climbing gear over multiple generations.

It would appear however, that up to moderate falls, the involved forces are a miniscule proportion of the yield strength. It may be the case that at the amplitude (fall factor) typical of most falls (0.25-0.75) (BMC Technical Committee, 2009), there is negligible contribution to fatigue of the high strength alloys used in climbing gear. This suggests that the only realistic cause of failure is catastrophic loading that exceeds the yield strength of the material.

3.7 Estimations of climbing fall frequency

Following on from **3.3**, some statistical analysis can be conducted to determine the likely frequency at which climbers fall. The web community UKClimbing is the largest database by which British climbers log climbs along with the associated style of climbing, grade of route and date of ascent. This resource has been used to compile the following statistics relating to climbing fall frequency (UKC, 2018):

a) Total logged climbs on UKClimbing = 5,393,779
  - Of which 3,008,860 were traditionally protected

b) 142,624 falls taken (of unknown severity and climbing style)

∴ Number of trad falls taken = 142,624 x (3,008,860/5,393,779) = 79,561 falls

This averages to one fall for every 38 climbs logged. If an average number of climbs could be calculated per climber over their lifespan, then these frequency values could be related to the results of a reliability test. This could provide an estimation of the longevity of nuts in relation to a human lifespan.

The following considerations detract from this analysis:

1. It is assumed that the number of trad falls is in exact proportion with the ratio of trad climbs to total climbs logged - this is unlikely to be the case. (Trad climbing is one of the climbing disciplines where falls are rarest, unlike sport climbing which is likely to have a disproportionately greater number of falls)
2. The severity of the falls is unknown.
3. Many climbers do not log falls out of embarrassment.
4. UKC does not discriminate between climbs performed for purely recreational, professional or performance purposes.
5. The statistics used do not distinguish between a multi-pitch or single pitch climb. A pitch is a rope length's of climbing. Therefore, an even weighting of logged climbs would be unrepresentative of the actual amount of climbing completed, as a multi-pitch climb may consist of up to 20 individual (single) pitches or more.

When considering the values overleaf, obtained from the database of the Mountain Training Association, further values can then be found for the number of likely falls that a climber would encounter in their lifetime (taken to be 40 years' worth of climbing):

Most recorded trad climbs completed by an individual in one lifetime: 5,615

*The above figure has been chosen as an upper bound to provide a safety margin for the average individual climber.

Considering a fall rate frequency of 1 fall for every 40 logged climbs, this equates to roughly 140 falls over a life time. Evidence suggests that half of all protection placed is passive and so takes the form of a nut anchor (BMC Technical Committee, 2009). Consequent expected stress and cycling to be encountered by a rock climber over a lifetime = average fall force of 6kN for 140 cycles. This statistic provides the underlying basis for the cycling parameters in the fatigue analyses conducted later in this report.

*All climbing statistics are derived from the recreational database UKClimbing.com (UKC, 2018) and the Mountain Training Association community logbook (MTA, 2018).

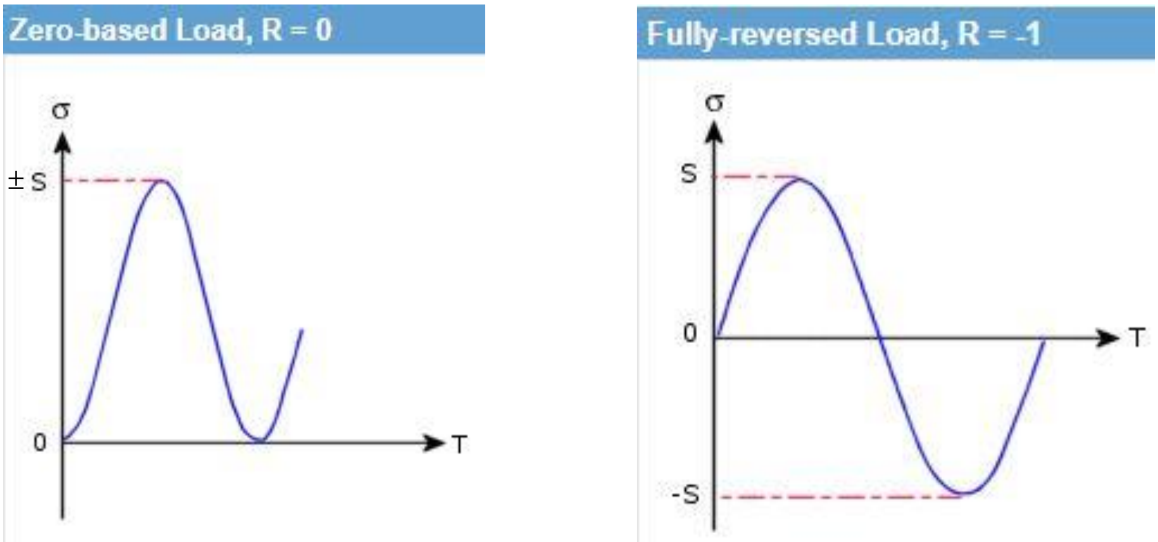
3.8 Further Fatigue Theory and Damage Accumulation

3.8.1 Introduction

This section will aim to build upon the previous investigations into climbing frequency, stresses and fatigue theory in order to provide a basis and justification for the numerical analyses and simulations in the next chapter. Specifically, investigation is made into the types of fatigue cycling, the methods used to assess cumulative damage and finally, how this can be combined to produce quantitative estimates for the lifespan of a component.

3.8.2 Types of Fatigue Cycling

There are two broad forms of fatigue cycling: zero-based fatigue loading and reversed fatigue loading. Zero-based loading refers to loading that occurs only in one direction before the test component is left to rest between cycles. Reversed loading refers to loading that occurs in one direction at a set stress magnitude and then reverses direction to reach the same peak magnitude in the negative direction, relative to the original load. In climbing use, the force of a fall does not alternate between the upward and downward directions. The loading chosen for this project is therefore consistently zero based in nature, throughout all simulation and practical test design phases. **Figure 6** below, provides a graphical representation of the difference between zero-based and reversed loading.



(a) **(b)**

Figures 6 (a) and (b): Graphical representations of zero-based and reversed fatigue loading (Solid Solutions, 2010)

3.8.3 Evaluation of Fatigue Analysis methodologies

Consideration of the basics of fatigue theory falls short of the knowledge required to effectively analyse the fatigue behaviour of a component. Three broad fatigue methods exist for fatigue analysis; the SN method, the EN method and the LEFM method. The SolidWorks software, by which the analysis in this project will be conducted, operates solely by the SN method (Solid Solutions, 2010) but evaluation of all methods has been performed nonetheless, to identify the suitability of the software in addressing the project aim.

3.8.3.1 The SN method (Stress vs Life)

The SN method is the most widespread form of fatigue analysis, and that by which SolidWorks operates. Prediction of fatigue life is based on extrapolation of the SN curves of the constituent materials to linear damage analysis **(3.7.4)**. This method is most appropriate to high cycle fatigue (> 10,000 cycles). Considered the most reliable method due to the greater existence of fatigue data produced through this method, it is also known to most precisely represent the fatigue behaviour of ductile metals like aluminium such as in this project (Lee, et al., 2005).

3.8.3.2 The EN method (Strain vs Life)

The EN method is typically reserved for low cycle fatigue and the study of polymer failure. Much less data has been produced using this method, so it is considered less reliable (Xiong & Shenoi, 2011).

3.8.3.3 The LEFM method (Linear Elastic Fracture Mechanics)

The LEFM theory focuses on crack growth rates. These provide accurate criteria for catastrophic failure of brittle materials but are limited with regards to plastic deformation, which typically occurs in ductile metals (Gu, et al., 2007).

3.8.3.4 Discussion

Considering the above, it would appear that the SN method, when combined with relevant linear damage analysis, is the most appropriate analysis method for this project. It is considered the most reliable; this is important to climbing use given that it is safety critical. It is also most appropriate for the plastic deformation encountered by ductile metals such as aluminium, which nut anchors happen to be constructed from. Lastly, this method is the only one encompassed by SolidWorks software, which is the only such software available for analysis under the resources available to the ES327 project. For all these reasons, the SN method has been chosen as the definitive tool for fatigue analysis throughout this project.

3.8.4 Damage Accumulation Theory

The following theory underpins the simulated fatigue cycling to be performed with SolidWorks. Damage accumulation theory refers to the tools used to analyse the effects of cumulative sequences of loading with regards to fatigue failure of a component. For a given load history, a proportion of the total life of a component can be calculated to have been consumed in relation to a defined threshold for failure.

There are two main models for cumulative damage, these are discussed below:

1. The Palmgren-Miner Linear Damage Rule

This is a linear model that is conditional on the fatigue stresses being constant in magnitude/ amplitude. With input from the data of an SN curve, each cycled stress on a component is calculated to have consumed a fraction of its life, in proportion with the data provided.

2. The Rainflow-Counting Algorithm

The method of Rainflow-counting is a tool capable of dealing with more complex loading histories. As opposed to the linearity of miner's rule, Rainflow counting is used instead for complex histories of variable amplitude loading. The process itself is an application of miner's rule to a matrix of discretised amplitude levels derived from the load history. As it is associated with complex and variable histories, analysis conducted by this method is considerably harder than with miner's rule.

3.8.4.1 Selection of an appropriate method for software testing

After consideration of both cumulative damage models, it was decided that a linear model (miner's rule) would be adopted for the purposes of the testing conducted in this project. Consequently, all fatigue analysis was operated under loading conditions of constant amplitude or magnitude. This would relate to certain stresses derived from FEA studies conducted at set magnitudes of external loading (kN.) This method was chosen for the following reasons:

a) Climbing is a diverse and individual sport; making it impossible to choose a particular variable loading sequence that can thoroughly represent the fall history of all its participants. The estimations made in section **3.6** were produced using statistical averages that were derived from linear assumptions, therefore, a linear damage model is most appropriate for consistency in this framework.
b) Related to a), The application of constant stress loads greatly reduces the complexity of producing generic lifespan estimates for any component.

Palmgren-Miner Cumulative Damage Law

Below, in **Equation (3)** is miner's law for cumulative damage. This has been provided to allow consideration of the theory underpinning the numerical analyses that have been calculated by the SolidWorks software.

(3) $$\sum_{i=1}^{k} \frac{n_i}{N_i} = 1 ,$$

where n_i = number of cycles that have occurred at given stress amplitude and N_i = number of cycles that would cause failure at that amplitude

Considering the above, the software simulations will seek to virtually apply loads at set increments of magnitude between 2kN up to the rated strength of 12kN. With the application of miner's rule through SolidWorks, the number of cycles to failure will be calculated and from here, lifespan estimates will eventually be produced. These analyses along with the preceding

FEA studies are developed in the next chapter **(4)**, which presents the conditions and results of the software simulations conducted under this project.

4 Software Simulations and Analysis

4.1 Introduction

This section encompasses the software simulations used in attempting to determine the failure modes and fatigue characteristics of nut anchors. This consisted of preliminary FEA and subsequent fatigue analysis. The fatigue analysis was based on cyclical stresses derived from the FEA results. The software used was SolidWorks and analysis conducted through the static and fatigue study tools.

4.2 Finite Element Analysis

FEA is a computer simulation tool which can resolve for physical quantities in complex 3D models. The quantities of interest to this project are the stresses resulting from externally applied loads (i.e. a falling climber). To determine the likely stress distributions and hence failure modes of a nut anchor, a 3D model of a DMM size 6 nut was constructed, with both the Al wedge and galvanised steel cable. The wedge was constructed from an extruded boss with appropriate tapers and fillets applied. Circular extruded cuts were made for the drilled cable slots with the cable taking the form of a swept boss. The wire was initially modelled as one-piece full-strength loop.

Three inaccuracies were intrinsic to this first round of simulations:

1. The modelled cable was formed as one solid cable whereas in practice it is a revolved wire rope consisting of multiple strands.

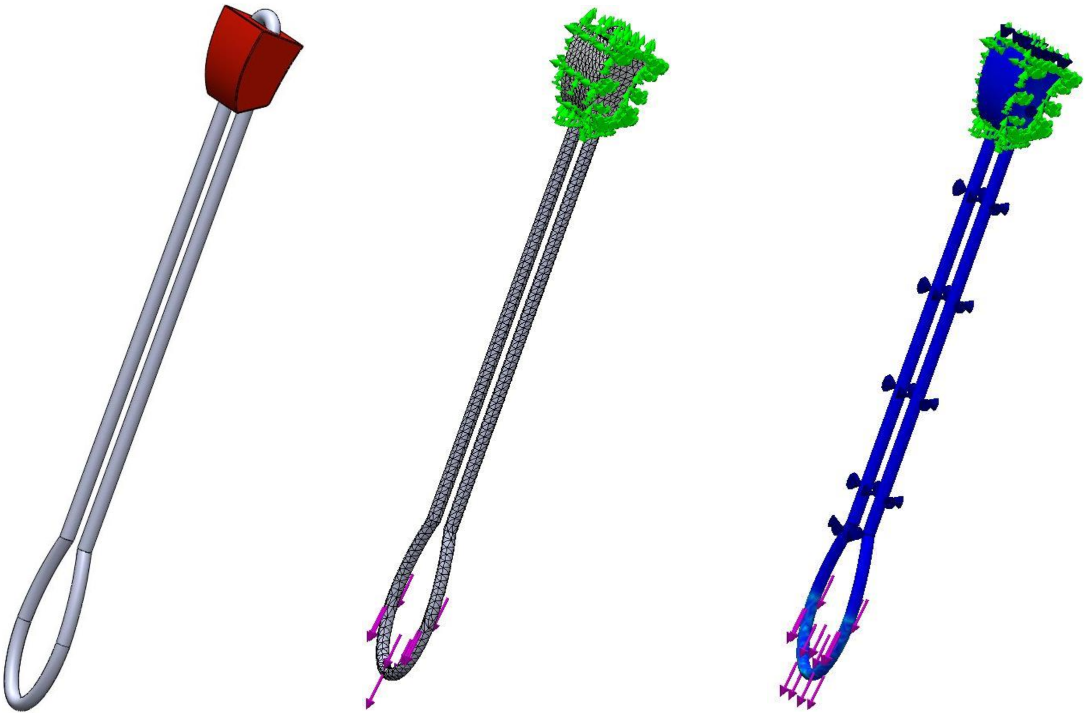
2. The modelled cable was closed and not an open loop terminated by a swage, as in reality.

3. Simulations were initially conducted with the assumption that all the wedge faces would be fixed. This represents only one fixture scenario where multiple occur in actual nut placements. In climbing use, nuts are also typically placed with two opposite faces in contact with the rock, with two further orientations derived from this.

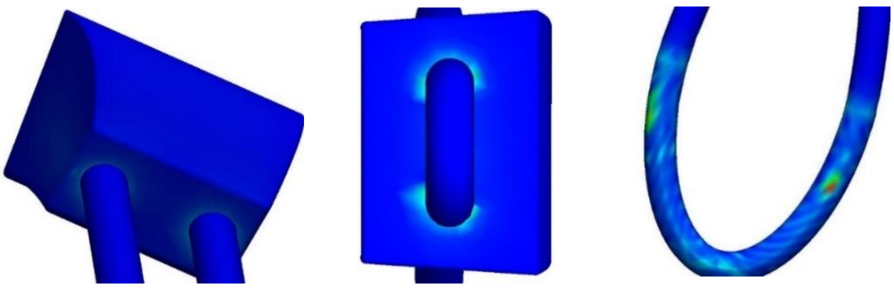
All these points suggest that the modelled nut would be stronger than a real one due to there being more material, no crimp joint and a firmer fixture. Further simulations **(4.2.2)** and **(4.2.3)** were then attempted to investigate the addition of a crimp joint and varying fixtures, respectively.

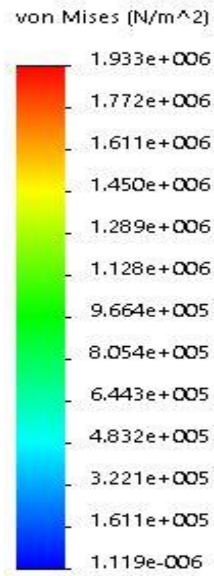
4.2.1 Initial FEA results

Boundary Conditions: Model Type = Linear Isotropic, Failure Criterion = Max Von Mises Stress, Component Contacts = No penetration, surface to surface (between wedge and cable)



Figures 7 a-c (left to right): 3D wallnut model, a) plain, b) with mesh, c) after FEA





Figures 8 a-d (left to right): areas of greatest stress concentration, a) at the slots on the bottom face of the wedge, b) similarly on the top face of the wedge c) at the bottom section of the cable, d) legend for magnitudes of stresses.

Table 5 [a]: material strengths for comparison to FEA results (all N/m^2)

Material	Yield Strength	Fatigue Strength	Max FEA Stress
7075 -T6 Alloy	5.03e + 008	1.60e + 008	4.83e + 005
Galvanised Steel	4.70e + 008	1.70e + 007	1.93e + 006

As can be seen from **Figure 8,** the areas of greatest stress concentration lie at the drilled slots for the cable and at the bottom end of the cable itself. These represent some of the aspects of the nut that have the smallest cross-sectional area and hence greatest susceptibility to stresses. The peak stresses at these areas are of the order 0.5 to 2 (e + 006) N/m^2 or 0.5 to 2MPa.

These values pale in comparison to both the yield strength and fatigue strength of Al 7075 alloy, approximately 500MPa and 160MPa respectively (Granta Design, 2017). In the instance of the 2MPa peak stresses corresponding to the red areas in **Figure 8,** the proportions to the yield strength and fatigue strengths are 0.4% and 1.25% respectively.

These numbers suggest that at the rated load of 12kN, the nut is not likely to fail due to mechanical load, either static or cyclical. Particularly given that these loads are below the fatigue strength. These results are at odds with the reality of the behaviour of nut anchors. They have been known to fail, as consistently mentioned throughout the introduction and in technical failure reports from the BMC. It is important to note that with the modelling assumptions made, there is good reason for this discrepancy.

4.2.2 FEA conducted with open loop and cable swage

The lack of the crimp joint increases the strength of the assembly, beyond anything realistically achievable. The presence of the crimp joint arises from the fact that the cable must form an open loop for it to be threaded through the nut in the first place. For nuts to be manufacturable, they therefore must have such a joint (DMM, 2016). Because of this, further simulations were conducted with the nut having an open loop cable and the crimp joint modelled to mimic the swage on real nuts. This was done with the use of a shrink fit and an enclosing ferrule made of Al 5052 alloy (Talurit AB, 2015).

The result of these further simulations was to present much higher stresses. The peak stresses shown in **Figure 9** (overleaf) are of the order of 40GPa. These are in excess of the yield and fatigue strengths of the 7075 alloy and even the yield strength of galvanised steel

(Aalco , 2017). These results imply that the 12kN rating for a size 6 nut is insufficient and that the equivalent stresses of this load are greater than what the design can accommodate.

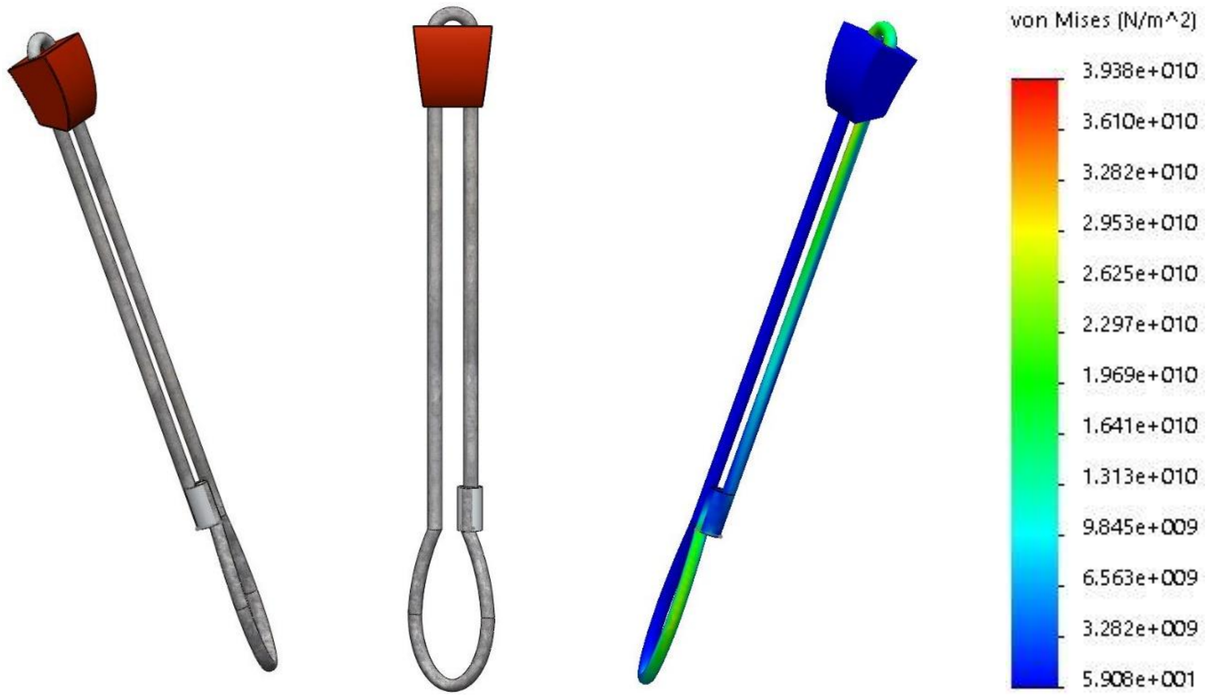
It is important to note that the inaccuracy of modelling the cable as one solid piece remains. The cable is realistically a stranded wire rope consisting of multiple interlocking strands, yet this was found to be unfeasible to model due to the difficulty in making a stranded wire concentric with the inner slots of the wedge.

This would imply however that the model would prove stronger than the real component. This is contradicted by the FEA results suggesting that the model is in fact weaker, as the GPa magnitude stresses computed are well in excess of the known strengths and characteristics of the materials comprising the nut anchor.

It is possible that these large modelled stresses result from cantilevered loading of the bottom loop of the wire, from within the crimp swage. The simulations conducted with the crimp swage were found to be unreliable and inconsistent. Errors were repeatedly encountered with regards to the boundary conditions involved with the joint formed by a crimp swage.

These are discussed in the next section **(4.2.3)**. The results overleaf in **Figures 9 & 10** are the only ones obtained throughout many attempts at stress analysis. Further simulations assume the swage-less model, and it is these studies that were taken forward to conduct numerical fatigue analysis.

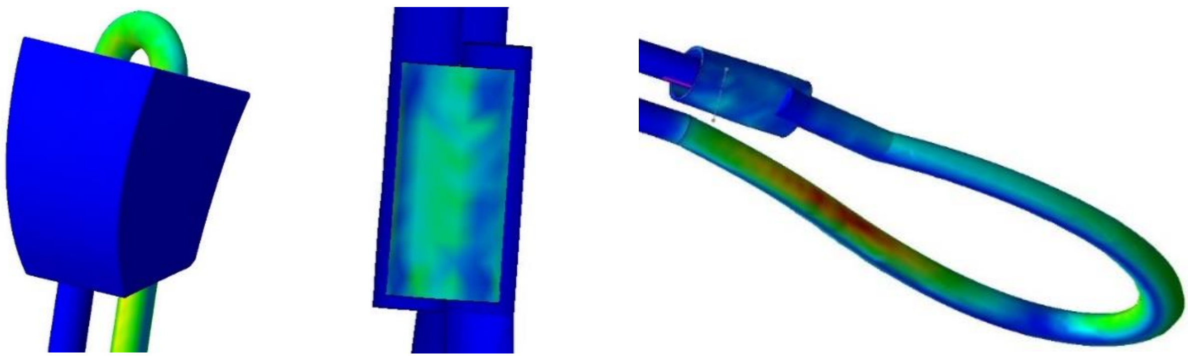
Boundary Conditions for analysis of model with crimp swage: Model Type = Linear Isotropic, Failure Criterion = Max Von Mises Stress, Component Contacts = No penetration, surface to surface (between wedge and cable), Further Contact = shrink interference fit (between the two cable ends and the swage ferrule)



Figures 9 a-d (left to right): 3D wallnut model, a) with crimp swage joint, b) front view of a), c) with FEA, d) legend for magnitudes of stresses

Table 5 [b]: material strengths for comparison to FEA results (all N/m^2)

Material	Yield Strength	Fatigue Strength	Max FEA stress
7075 -T6 Alloy	5.03e + 008	1.60e + 008	59.08
5052 Alloy	1.93e + 008	1.70e + 008	59.08
Galvanised Steel	4.70e + 008	1.70e + 007	2.63e + 010



Figures 10 a-c: (Left to right) a) stress concentrations in upper cable loop, b) in the crimp swage (c) in the lower cable loop

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	2.15938 mm
Tolerance	0.107969 mm
Mesh Quality Plot	High

Total Nodes	15938
Total Elements	8706
Maximum Aspect Ratio	19.533
% of elements with Aspect Ratio < 3	94.3
% of elements with Aspect Ratio > 10	0.172

Figures 11 a-b: Mesh information and further simulation parameters **(Solid Solutions, 2010)**

4.2.3 Discussion of Boundary Conditions

The disparities between the various simulations highlight that there is great variability in the simulations. This was, in part, due to the specific boundary conditions chosen for each round. Two major challenges were encountered in terms of a) the interactions between the wedge faces and the mimicked constriction/wall b) interactions between the cable and wedge. These are considered below:

a) To represent the type of loading that occurs when a nut is pulled through a constriction, the faces of the wedge that would be in contact with the rock were set as fixed in place. However, this does not allow for the wedge to stretch, so only certain stresses were developed by the FEA. These occurred in the swage, cable and wedge corners yet realistically deformation of the wedge itself should also take place. Though different wall – wedge interactions were attempted, the fixed geometry was chosen due to the dependence of other fixture methods on mechanical properties relating to the constriction or exterior wall. This was deemed unfeasible due to the challenges presented by the immense variability of these properties between different rock types.

b) As in **4.2.2**, load simulations with the swaged model proved difficult with studies taking up to two hours or more, to resolve the interference contacts arising from the modelling of the crimp swage. The shrink/interference fit attempted is a proven practical joining method but one that was found to be very difficult to implement in SolidWorks. The unlikely results presented by the simulations further prove the limitations in attempting to model this loading.

4.2.4 FEA simulations with varying fixture orientations

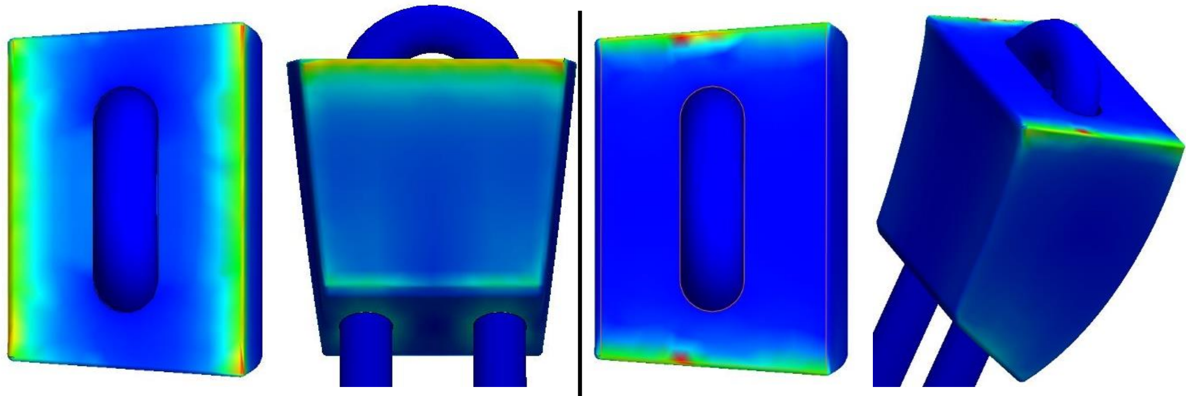
The previously attempted FEA simulations assumed that all the faces of the wedge were fixed, representing an all-enclosing rock feature. Though naturally possible, these are very rarely found in rock climbing. Further simulations have therefore been conducted to more realistically represent the common orientations of nut anchors in their use. Two common orientations exist for nut anchors and for the purposes of maintaining reasonable scope, only these are considered **(Ward, 2017)**. These two orientations are in the normal direction (largest wedge faces in contact i.e. fixed) or sideways (smallest wedge faces fixed).

Figures 12 a-b: (left, a) red nut anchor loaded in the normal orientation (right, b) lilac nut in the sideways orientation

Table 6: Peak stresses under varying applied loads and orientations

	Peak FEA stress (MPa)	
External Load (kN)	Normal Placement	Sideways Placement
2	67.3	272
4	135	544
6	202	816
8	269	1,090
10	336	1,361
12	404	1,630

As can be seen from **Table 6** above, nuts appear to be significantly weaker in their sideways orientation. The peak stresses are approximately four times greater in this orientation than in the longitudinal ones. This corresponds to best practice in trad climbing, which seeks to minimise the use of sideways placements when normal ones are possible. The reduced area of contact presented by the smaller wedge sides results in greater pressure and hence stresses on both the nut and the constraining rock feature.



(a) (b)

Figure 13: Stress concentrations in (a) normal and (b) sideways orientations

4.2.5 Evaluation of the framework by which FEA was performed

Though quantitative results were obtained throughout the many iterations of FEA studies, there were systematic errors in the way in which they were conducted. Typically, FEA is performed with initial simulations of a reduced (coarse) mesh size. This allows for immediate identification of areas of interest in the model, such as stress concentrations. Localised refinement of the mesh can then be made within these areas of interest, as tighter meshing allows for more precise analysis and less error.

Within this project however, the mesh size was kept constant at the medium value permitted by SolidWorks FEA in relation to the tightest, or coarsest possible mesh sizes. This was in part, because tighter mesh sizes increase the power requirements and computation time needed. This was particularly notable with the simulation performed of the nut model with swage, which alone, took 2 hours and 37 minutes to complete. In contrast, simulations on the swage-less models typically took between 30 and 40 seconds, with a further 20 seconds for each of the fatigue computations.

4.2.6 Discussion of FEA results

The results presented by the analysis of these different 3D models are quite varied. The model without the swage was seen to be overly strong in relation to the incurred stresses whereas the model with the swage was overly weak (In relation to the manufacturer's kN rating). The stress behaviours found under different orientation were as expected however. Stress concentrations were found towards the expected smaller areas on the wedge and at the cable, particularly in the parts of the cable where bends were most sudden (at the wedge thread points and at the bottom loop). The wedge stresses were found to be dependent on orientation where the magnitudes were greater for the same load, on sideways oriented nuts.

Problems have arisen with the difficulty in modelling a crimp fitted swage in SolidWorks in relation to the boundary constraints of FEA simulations. Fatigue analysis (**4.3**) has been attempted nonetheless in the next section, but only in varied orientations with the swage less model. The need for practical testing is emphasised by these inherent modelling inaccuracies. Therefore, the results provided represent a theoretical upper bound that cannot be realised with actual nut anchors, as they require the swage to exist as a manufacturable product.

4.3 Fatigue Analysis

4.3.1 Introduction

This section builds upon the FEA conducted to simulate fatigue cycling of a load upon a component for a given number of cycles. The idea of this is to virtually replicate the loading of a nut anchor in a tensile testing machine over thousands of cycles when this would be time consuming in a practical laboratory. The tool used was SolidWorks Fatigue analysis which relies on static FEA studies for stress data.

4.3.2 Parameters and Methodology

Following on from the FEA results, fatigue analysis was conducted. This occurred in SolidWorks as an extension of the FEA study, whereby the loading simulated in the FEA was cycled according to set parameters for fatigue simulation. These parameters consisted of the magnitude of the stresses experienced by the nut and the reversal nature by which these stresses were applied. The initial model was of zero-based constant amplitude loading with stresses corresponding to the various FEA tests with magnitudes of 2, 4, 6, 8, 10 and 12kN.

The FEA study chosen for fatigue cycling was that of the swage-less model. This was ultimately due to the difficulties presented by the crimp swage in providing stable boundary conditions for stress analysis. The FEA simulations conducted with the crimp swage were unreliable with frequent numerical conflicts relating to the surface contacts between the cable and wedge. As they are derived from the swage less model, the resulting lifecycle estimates are therefore very much a theoretical upper limit that cannot be realised with actual anchors.

Limitations of Fatigue Analysis

An important limitation to the accuracy of this analysis is that SolidWorks Fatigue Analysis cannot calculate lifespan/cycle predictions when a combination of two FEA studies are used. It is therefore impossible to account for the use of both normal and sideways placements throughout a particular lifetime (even though both are realistically used repeatedly throughout the use of the same anchor). It is also impossible to consider the damaging effects of wear in the removal and placement of nut anchors by the climber and second.

4.3.3 Results

Table 7: Lifespan predictions for a size 6 nut anchor with differing orientations and magnitude of applied loads

	Minimum Number of Cycles to Failure		Number of Human Lifetimes to Failure (x 140 cycles)	
Applied Load (kN)	Normal Placement	Sideways Placement	Normal Placement	Sideways Placement
2	1.00×10^6	1.00×10^6	7142	7142
4	1.00×10^6	1.79×10^4	7142	128
6	1.00×10^6	7.00×10^3	7142	50
8	1.00×10^6	7.00×10^3	7142	50
10	1.00×10^6	7.00×10^3	7142	50
12	3.79×10^5	7.00×10^3	2707	50

4.3.4 Discussion

Table 7 above, displays predictions for the lifespan of a size 6 wallnut under varying conditions of applied load and fixture. The results were calculated through simulated fatigue cycling of the corresponding FEA studies. This was performed with computerised linear damage analysis through the SolidWorks Fatigue Analysis software. These particular results have been isolated in the interest of maintaining the scope of the project. Though displacement and strain are relevant factors to fatigue failure and indeed crack propagation, they have been ignored as they do not give an immediate indication of how the longevity of an anchor relates to the magnitude of load applied. The shown relationship between load and lifespan satisfies part of the project aim, to allow for more precise guidelines for climbers, in terms of the use of their nut anchors. Analysis of the implications of these results is provided overleaf, **4.3.4.1**.

4.3.4.1 Implications of Fatigue Analysis Results

According to the results in **Table 7,** in nearly all instances, the lifespan of a sideways placed nut is considerably less than that of a normal one. In terms of the number of cycles, this disparity is nearly two orders of magnitude at loads less than 12kN.

At the load of 2kN, both orientations provide a large lifespan, suggesting that static or near static loading of anchors does not accelerate failure in any meaningful way. In such use, regular loading would be derived almost solely from static anchor building and belaying practices. The significance of this is that climbers who do not fall regularly, do not really have to worry about the longevity of their passive hardware. Furthermore, nuts used in the normal orientation, appear to be very durable up to their rated load, even in circumstances of high factor dynamic falls.

The consistent lifespan of 10^6 cycles for lower loads on normally placed nuts, implies a fatigue strength corresponding to loads of between 8kN and 12kN. Part of the project premise was that despite high ratings of 12-14kN, protection was much more likely to fail at lower forces such as those from average falls (5-7kN). This has proven to be unfounded, as a fatigue strength is indeed evident where there was not thought to be one. This could be due to the high–strength nature of the aluminium alloys present in climbing protection, with much reduced fatigue susceptibility.

However, the lowest predictions are presented by the continued use of sideways nut placements. Here, the predictions in terms of a likely lifetime's worth of climbing, are relatively very low. This would be of concern to outdoor centres and instructors, where the use of gear to 7000 cycles or 50 lifetime's worth of climbing is foreseeable. This is important to realise, on the part of the climbing community, as failure is a more realistic prospect. As such, if a practical test was to confirm this, guidelines should be provided to nut users that explain the reduced durability from loading in the sideways orientation.

5 Practical Test Design

5.1 Methodology Selection

Considering the results of the 3D FE and Fatigue analyses, along with the conflicts encountered with the differences between swaged and swage-less model, a practical test should be devised to correlate between a real nut anchor and the virtual models. For such correlation to occur, the test should follow a methodology consistent with the original software simulations. The chosen cycling was that of zero-based loading, as this was most representative of the directional loading inherent to climbing use.

The software tests conducted were representative of the methodology of constant stress testing, as the load magnitudes were kept constant until failure. For a practical test to be instigated successfully, it should therefore involve zero-based loading, with stresses of constant magnitude. To relate to the performed simulations, a separate constant-stress test must then occur at each of the set stress magnitudes, requiring 6 nut specimens for each stress increment corresponding to loads of 2kN up to 12 kN.

5.2 UIAA Practical Test Requirements

Overleaf in **Figure 12,** is an excerpt from the EN-12270 standard for nut anchors, which have been alternatively termed chocks. It details the relevant wedge widths, in relation to the corresponding widths needed for the vice jaws used for testing. These represent a constriction similarly to how nuts are placed naturally. For a UIAA test, a nut is placed in an appropriately sized vice and pulled through with a tensile testing machine at a set magnitude of load, kN. The individual wedge dimensions should be noted, in relation to the required vice sizes.

For a practical fatigue test to be developed in accordance with the UIAA test yet with the methodologies specified by the results of this project, little would need to be changed. The tensile tester needs to be capable of being cycled but in such a way to ensure that the loading remains zero-based. The range of loads allowable by the tester would also have to correspond to the magnitudes chosen for the simulations. To correlate between the virtual tests performed in this project, and the proposed practical test, the same variables must be maintained. Therefore, the same loads of 2, 4, 6, 8, 10 and 12 kN should be applied to separate nut anchors (for each stress magnitude) until failure. This should be conducted for the two common orientations (normal and sideways), requiring a total of 12 separate anchors for the test.

When considering the combined instances of fixture and load, there are in effect 12 separate, individual fatigue tests to be performed for the aims of the project to be adhered to. This encompasses, in effect, one practical fatigue test for one size of nut anchor. For further testing to occur with other sizes, this procedure must be repeated with a further 12 specimens for each size of anchor. If an accurate scaling factor was calculated between sizes, further practical testing (of other sizes) may not be necessary but such testing may be needed to devise this scaling factor in the first place.

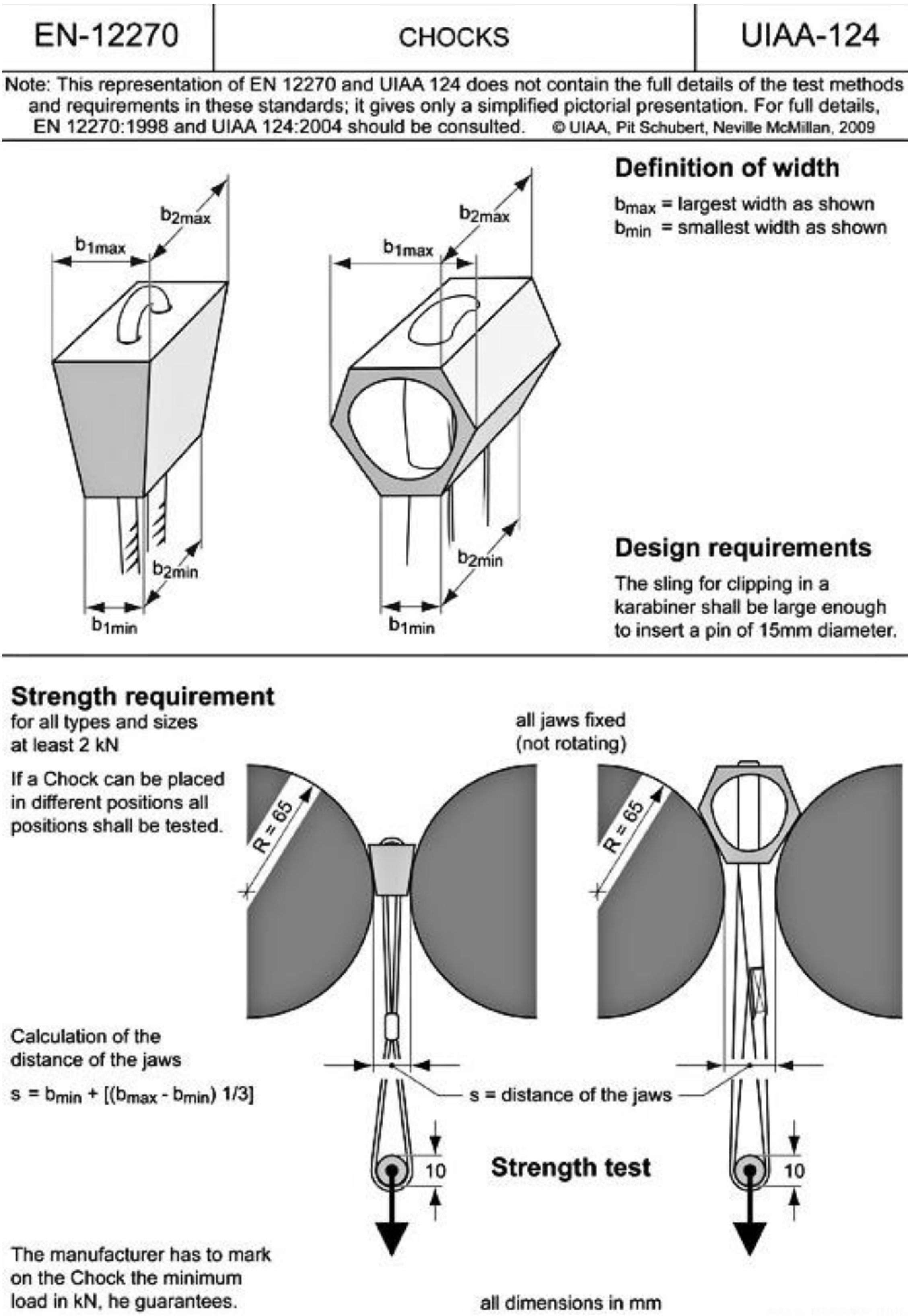


Figure 14: Practical Tensile Test Apparatus for Passive Anchors **(UIAA, 2017)**

6 Conclusions

The following three objectives were set for this project, and it is the aim of this section to verify whether they were met or not:

1. *Investigate failure modes arising from the combination of impact damage and fatigue with regards to the continued use of passive climbing protection.*

With the assumption made that areas of greatest stress concentration would correspond to likely points of failure; this investigation was carried out in two parts:

i. Initial rudimentary predictions of stress concentrations based merely on geometry **(2.4)**
ii. The later quantitative stress analysis conducted through SolidWorks FEA **(4.2)**.

Despite the errors intrinsic to some of the FEA studies, the stress concentrations found throughout were found to be accurate in relation to the initial predictions. These were found to be at the upper corners of the wedge, although the fixture orientation of the wedge was important in determining which corners were most affected. Further concentrations were found in the cable swage and cable thread points, as originally predicted in the preliminary chapters.

2. *Conduct FEA using 3D models of current protection with further use of software for fatigue analysis and degradation testing.*

SolidWorks software simulations were carried out and established stress concentrations along with lifespan estimates obtained with virtual fatigue cycling. The fatigue cycling assumed constant amplitude loading for simplicity, given the known average climbing fall force. These were virtually simulated until failure with the results being a defined number of cycles to failure. These were key results in that they partly satisfy the core aim and premise of this project, being to estimate the longevity of nut anchors.

The estimations achieved were then related to typical climbing fall frequency **(3.7)**. Product lifespans were then established in terms of a statistical lifetime's worth of climbing. These results were found to be large for normally oriented nuts (of the order 10^6 cycles or roughly 7000 statistical lifetime's worth of climbing) right up to the rated strength of 12kN. The implication of this being, that normally placed nuts are not particularly susceptible to fatigue failure when considering the use they are subjected to in rock climbing.

Conversely, sideways nut placements were found to be considerably weaker. At loads of 4kN, they were found to fail at 17,400 cycles, reducing to 7000 cycles at loads greater than 4kN. This is concerning when related to lifetimes, resulting in 128 to, as few as, 50 lifetimes respectively. This can begin to approach the usage encountered by nut anchors in regular group use such as with outdoor centres and climbing clubs. Guidelines should be implemented accordingly, so that climbers are aware of the weaknesses of sideways nut placements.

Despite the existence of these numerical results, it is worth remembering that they are very much limited by the accuracy of the FEA studies. A safety factor to correlate between the model with swage and the model without, could not be established. Therefore, it is impossible to quantify the error intrinsic to the lifespan estimates. All that is known, is that they are a theoretical limit to the longevity of nut anchors. These results are therefore of limited real use, until they can be confirmed by practical fatigue testing. This needs to be considered when relating the results of this project to the wider world, without the context of further testing.

3. *Given both the findings of the failure investigation and software results, design a practical laboratory test to establish real limits of use of hardware with appropriate reliability test methodology.*

Despite the errors encountered throughout the software simulations, and indeed because of them, a practical test is all the more necessary. For such error to be quantified and for a safety factor to be established, a practical test should be performed with a methodology relating to that by which the virtual simulations occurred. This has presented a need for a practical fatigue test based on loading of constant amplitude corresponding to the stress levels produced in **Table 6** of the results. In terms of the methodologies investigated, this corresponds to a series of individual constant-stress tests, where the stress magnitudes are as mentioned.

Although investigation was made into many other reliability test methods than constant-stress testing, this has been found to be the only method that feasibly fits into the premise of this project. This was due to consideration of the linearity of the statistics available for climbing use, as well as the pre-determined methodology (constant amplitude fatigue loading) by which the computerised fatigue cycling occurred. The combination of these factors, along with the simplicity facilitated by the use of a linear damage rule, has meant that the practical test, that would result from this project should be a series of constant-stress tests.

In terms of the apparatus required, the UIAA test set-up should be used with the relation between jaw size and wedge width observed. A tensile testing machine should then cycle zero-based loads at each set increment, to separate specimens, until failure occurs. The point of failure should be considered to be the point at which a nut anchor can no longer withstand a load corresponding to its rated strength in kN. With the results of this test, comparison could then be made to those of this project. Consequently, appropriate usage guidelines should be compiled, to ensure a determinable result for the climbing industry and community.

7 Recommendations for Further Work

7.1 Finite element analysis

The simulation tools used in this project (SolidWorks FEA and Fatigue Analysis) are add-on tools to a primarily design oriented programme. This project has been limited by the capabilities of this software, though it is merely that which was accessible to the author. Further investigations conducted along the themes of this project might consider using dedicated software for FEA and Fatigue Analysis, with enhanced capabilities. The use of dedicated analysis software might allow for more certain results and understanding.
A few programmes which may fulfil such advancement are:

1. N Code – Design Life Analysis by HBM Prenscia (for more detailed Fatigue Analysis)
2. Abaqus Unified FEA software by Dassault Systemes (for more precise FEA study)
3. Weibull ++ Simumatic (for improved statistical design of a practical reliability test)

Improvement may also be made to the framework in which the current FEA studies were made. Further work on these simulations could develop this project's aim and perhaps yield completely different results, especially if the following improvements were implemented:

(a) A methodical approach was taken to mesh refinement within simulations. Further time could also allow for more detailed studies with particular attention to convergence error for more precise results.

(b) A wider range of boundary conditions were applied; particularly in relation to attempting to model the crimp swage on a nut anchor, and the interactions between the alloy wedge and the constriction representing the rock feature. These two conditions were the greatest limiting factors in providing accurate simulations in this project.

7.2 Practical testing under dynamic loading conditions

The existing UIAA standards for tensile testing of climbing anchors detail the application of a static load to an anchor. The magnitude of the load is chosen to be equivalent to a roped dynamic load corresponding to a given fall factor. Through the methods mentioned in the introduction under ‘rope theory’, the equivalent loads can be calculated. The approximation of a static load to a dynamic one is reliant however, on mathematical models that are still not closely representative of dynamic rope loading behaviour. The following methods provide a means of practical testing that is more representative of real climbing use:

1. The use of a drop tower as done by many manufacturers of climbing hardware. For a given fall factor, a weight attached to a length of dynamic rope can be dropped to mimic a climbing fall. This allows for consideration of the differences between static and dynamic loading. This still does not consider climbing factors such as the dynamic frictional effects of rope slippage from the belayer and the differences between the forces incident upon rigid test masses vs deformable human bodies.

2. Field testing i.e. actual roped fall testing whilst rock climbing. Though most realistic, it is the least repeatable method as it would be almost impossible to ensure identical braking effects between falls. There is also massive variability in the environmental conditions relating to constrictions in rock, the integrity of the rock etc. Below is a full consideration of the limitations of field testing:

   a) There is an inherent safety risk to the climbers involved, considering that the aim of the test is to cause failure of their protection.

   b) Repeated use of the same feature may cause damage to the rock involved. This conflicts with the repeatability of the experiment and raises environmental concerns in terms of the sustainability of such testing. This is particularly important in terms of preservation of the rock available for climbing.

   c) The implications of real-time fatigue testing are that the process of product design will become tedious, costly and require thousands of hours to attain the desired limits of use, for what is an intentionally durable product. This is, of course, why reliability tests are carried out in place of real time tests in the first place.

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