An Analysis of the Risks Associated with the Fixed Rock Climbing Protection Proposed for Installation by the Climbing Community at Kangaroo Point (North)

And

A Specification and Maintenance Schedule for such an Installation

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1. Executive Summary

A section of the Kangaroo Point Cliffs, at their northern limit (KPN), has been closed to recreational rock climbers for over a decade. Past discussions with the Brisbane City Council highlighted that one of the barriers to reopening this section of the cliffs to climbers is the public liability that attaches to the small rock anchors that climbers install so as to be able to climb with safety.

This document provides a detailed analysis of the risks associated with such climbing infrastructure as would be installed at KPN. It concludes that the use of hardware compliant with European standards for climbing anchors would reduce the occurrence of severe harm arising through the failure of such infrastructure to an unmeasurably low rate. It shows that the inspection requirements necessary in order to maintain this level of security are easily achieved.

It should be clear that in permitting public recreational climbing at KPN, Council is not adding a disproportionate public liability burden compared with the other outdoor activities it currently sponsors.

2. Technical Abstract

This analysis concentrates solely on the hazards associated with the failure of climber-installed, cliff-infrastructural components. Known climber behaviour is used to arrive at safety integrity targets for each class of infrastructure. Both current and ultimate, worst-case forward projections are used. The safety integrity targets are defined probabilistically as the rates of failure on demand (PFDs) that must be met if accident rates are to be constrained to acceptable levels.

A probabilistic approach, based on a simple, mechanical model of the roped, climbing system is presented. This model allows a strength target to be set for any class of infrastructure. The results are shown to align with the European Standard, EN959, for rock anchors.

It is shown that current 'best practice' in the fixing of such infrastructure is adequate to meet the strength targets derived from the preceding considerations.

The analysis is extended to consider the maintenance requirements of such cliff infrastructure. The probabilistic approach allows an inspection/replacement interval to be set according to the number of stress cycles a specific item of infrastructure has accumulated.

3. Key Findings

- An ultimate, worst-case rate of the occurrence of severe harm of < 0.1 event per annum requires the PFD target for first bolts to be < 4 in 10^6 and for anchors < 5 in 10^7. Free of worst-case assumptions, the occurrence of severe harm associated with these PFD targets would be unmeasurably small at <0.0001 events per annum.
- The PFD target for first bolts is achievable with an EN959 compliant bolt. The target for anchors is easily achievable with an assembly comprising a redundant pair of EN959 bolts.
- Only the first bolt is likely to accumulate a number of stress cycles sufficient for fatigue phenomena to challenge its integrity. Even under worst case assumptions of extreme utilization levels, its service life will be in excess of 5 years.

4. Recommendations

- All single bolts to be Fixe #014-A 10mm x 80mm 304SS glue-in ring bolts. This bolt is EN959 compliant with a rated ultimate strength of 35kN.
- All bolts to be fixed according to current best practice with Powers PF Pro epoxy adhesive or similar.
- All anchors to be Fixe #393 SS V chain anchor. This product provides two EN959 compliant glue-in ring bolts and an EN12275 compliant carabiner.
- Single bolts to be inspected for wear and damage every 5 years.
- Anchors to be inspected for wear every year.

5. Introduction

By reference to climbing gym enrolments, we estimate that Brisbane has as many as 100,000 people who have 'tried' climbing at one stage or another. Further to this, we estimate the value of the current Kangaroo Point Cliffs to the climbing community is between $1M and $2M p.a., and that this figure is set to double over the next five years. Pressure on this limited recreational resource makes it attractive to open the small section of cliff to the north of the current cliff line which climbers call KP North (KPN).

However, both in Australia and overseas, it has been the case that the development of recreational climbing has been hindered by land managers' perceptions of the public liability burden that attaches to climber-installed infrastructure, in particular the so called 'bolts' that climbers use as a means of arresting a fall. The public land manager is in a bind in that they have an obligation to manage public assets for maximum value, yet at the same time, need to discharge a duty of care to the users of such assets.

Both overseas and within the Australian States, public liability legislation has been enacted to help free the land manager from the burden of public liability associated with certain 'risk' activities. In very many ways, such legislation is a necessary, though as we shall see, not sufficient, first step in allowing a sport such as climbing to prosper on the public estate.

Perhaps the biggest problem is the public perception that modern 'sport climbing' is a high risk activity. While it is inarguable that traditional forms of climbing, especially mountaineering, are dangerous, this certainly does not apply to the modern sport climbing discipline which is something quite apart. In France and Spain, the sport goes back two generations, and is now very much mainstream. Every year millions of men, women and children fall on literally tens of millions of bolts without there being a major issue with serious injury. The conclusion is inescapable that 'they must have got this right'; that this is a mature sport; that provided one uses European standard complaint equipment, this sport is no more dangerous than other challenging physical recreation.

So we ask, what burden of public liability does the Brisbane City Council accept by the act of opening KP North to the sport climbing community? Of course there are a number of aspects to this question, but in this analysis we will address just the one case that causes the most angst. What if a climber-installed infrastructural component such as a bolt were to fail resulting in death or a serious injury? It could be argued, and we believe, should be argued, that the climber knows they are participating in a potentially dangerous activity, and should not undertake such an activity without the knowledge necessary to avoid a potential source of harm such as a structurally inadequate bolt.

Although we consider all climbers should be bound by the forgoing caveat, it is arguably insufficient to discharge the duty of care of those installing cliff infrastructure. In our opinion there is an immoveable duty on the installer to be aware of best practice, and to ensure that such is carried out.

Just how such a case would proceed through the courts is a matter apart, and ultimately of little importance if the chances of such an event happening can be shown to be very low. The purpose of this analysis is to demonstrate a method for arriving at an estimate of that probability of the hazard described above materialising, and from there arriving at formal specifications for the cliff infrastructure.

6. Glossary of Climbing Terminology

Anchor	A specialized item of cliff infrastructure located at the top of a climb and so designed that it is sufficiently secure to act as a climber's only support.
Belay	The act of a providing braking force on a climbing rope such that the fall of a climber is arrested.
Belay Device	A specialized device used to realize a belay.
Belayer	A person who, using a belay device, provides a belay.
Bolt	A specialized item of cliff infrastructure that the ascending leader uses to secure the climbing rope. It is designed to be one part of a multipart safety system, and is not, of itself, used as a means of

	ascent.
Carabiner	A snap link used as one component of the safety system.
Chains	Synonymous with anchor or anchors. Some anchors are constructed using lengths of chain.
Cleaning	The act of lowering the leader from the anchor, so that he can remove the quick-draws he placed at each bolt during his ascent.
Clipping	The act of the leader connecting the climbing rope to each bolt with a quick-draw as he/she passes.
Fall Factor	A measure of the severity of a fall. It is calculated as the fall distance divided by the total amount of active rope in the system.
Falling	If the leader loses contact with the cliff he/she falls twice the distance he/she is above the last bolt before his/her fall can be arrested by the belayer.
Leader	The person who is climbing from the bottom toward the top of the cliff with the climbing rope trailing behind him/her. He/she secures himself/herself by clipping the rope through quick-draws attached to bolts as he/she passes by them on the cliff face. A belayer on the ground provides a belay should the leader fall.
Leading	What the leader does.
Lower-off	When the leader reaches the top of a climb, he/she clips the anchor and is lowered off by the belayer. Often he/she will 'clean' the quick-draws on the way down.
Quick-draw	A piece of equipment used to connect the climbing rope to a bolt. It consists of two carabiners joined by a short length of sewn tape sling.
Sport Climbing	The most popular rock climbing style where the climber ascends the cliff using just quick-draws to clip the bolts installed in the cliff face.
Top-roping	A popular climbing style for novice climbers where the ascending climber is supported from above by a rope passing through an anchor and back to a belayer at ground level. In this mode of climbing the possibility of falling even a small distance is obviated.
Working	When a lead climber encounters a section that is beyond his/her capability, he/she may choose to 'work' the difficult moves by repeatedly climbing and falling.

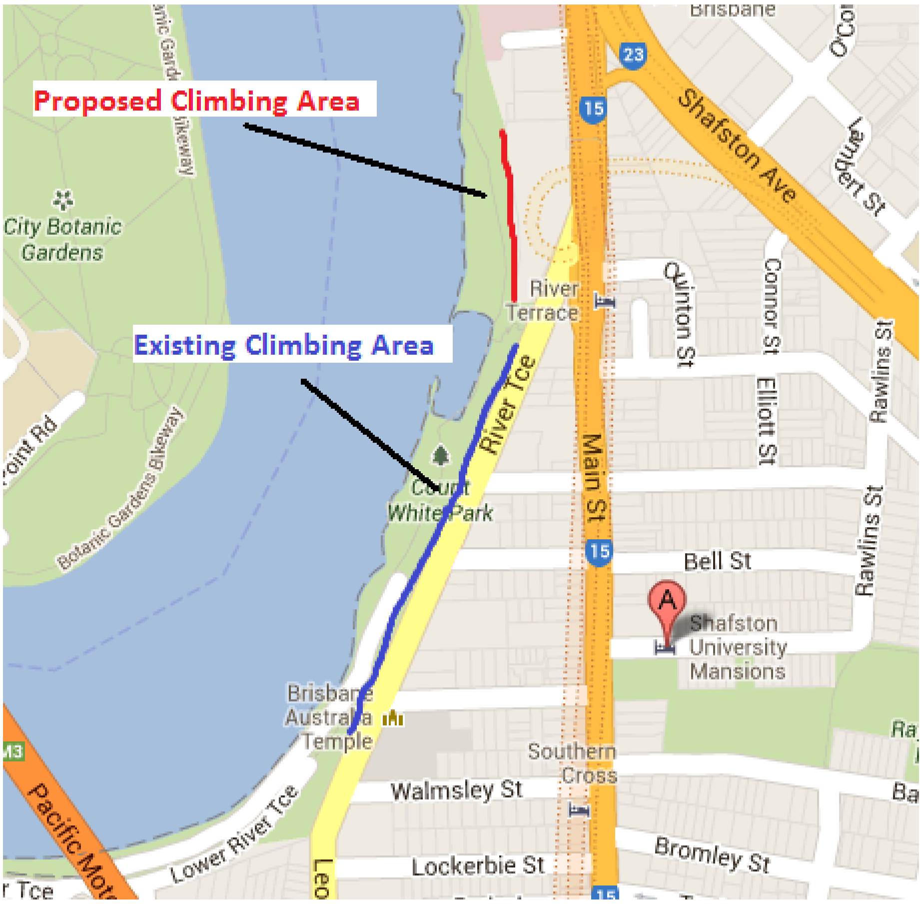
7. Glossary of Risk Analysis Terminology

Domain	A formal definition of the limits of the system under consideration, with all actors, and all hazard agencies enumerated.
Exposure	A quantitative measure of the degree to which a specified actor is in harm's way.
Functional Safety	A discipline that, amongst others, considers the use of 'safety functions', ie components that have no utility other than to constrain potential harm.

Harm	Physical injury or damage to health
Hazard	Potential source of harm
PFD	Probability of failure on demand
Risk	Combination of the probability of occurrence of harm and the severity of that harm
Demand	An asynchronous challenge to the integrity of a safety function

8. Location of Proposed Climbing Development

The location of the proposed development is illustrated below. This cliff-line to the immediate north of the cliff stairs, like the rest of the Kangaroo Point Cliffs, has a history of climbing going back decades.



This particular section of the cliffs was closed to climbing well over ten years ago due to concerns from the TAFE college located in the grounds immediately above the cliffs. However, with the demolition of the old college, and the development of the cliff-top park and cafe complex several years ago, the process of reopening the cliffs for climbing was begun with Council, and progressed as far as further stabilisation operations being carried out. All progress ceased with the 2011 flood.

View of the cliff-line looking north from the access stairs

9. Domain Definition

a. The hard geographic boundaries of the domain are the north-south running cliff-line on the east, and the Brisbane River, some 50m away, to the west. The section of cliff suitable for recreational climbing starts some 50m north of the access stairs at the cliff-top café, and extends for approx. 90m further north.

b. Environmental
   i. Presentation
      1. Compact Brisbane Tuff quarry face approx.. 18m in height and substantially vertical in aspect.
      2. The cliff face has been stabilised by Brisbane City Council and is considered stable enough for climbing activities except for the very top which is unsuited due to a layer of soil and debris.
      3. The cliff top is unsuitable for access by the public due to the café and park infrastructure.
      4. The immediate surrounds are grassed parkland planted with small trees. A restricted access road, and a cycle way that merges with it runs some 3-4m from cliff base.
      5. Due to the park environment, many visitors within the proximity of the cliffs will be other than climbers.
   ii. Weather
      1. The temperature and humidity is conducive to climbing all day during winter.
      2. High temperatures during summer restrict climbing activities to early morning and late evening.

        3. Artificial lighting makes climbing possible at night all year round.
    iii. Cliff Conditions
        1. The cliff faces west … rock temperature can be as high as 30 -40deg by mid-afternoon.
        2. Humidity is high in summer months
        3. The rock is mostly dry, but can be subjected to running water during rain storms.
        4. There is run-off from café complex at one point along the cliff line.
        5. Proximity to the tidal river and sea means the environment should be considered mildly maritime.

c. User Groups: A number of user groups frequent the domain. Table 9.1 attempts to quantify how each of these groups interacts with those climbing. The residence time of most people within the domain is short, and while it is possible for non-climbers to stray into the region of concern along the base of the cliff, their residence time within this zone is likely to be short. Nevertheless we include the possibility that a small subgroup may remain as spectators.

group	**numbers within domain at any one time**	**residence time within domain**	**proximity to harm - closest approach (metres)**	**overlap with climbers (ie within region of concern)**
climbers	5 to 30	1 to 3 hrs	0	100%
cyclists	1 to 3	10 to 30 secs	4	0%
runners	1 to 10	60 to 120 secs	4	0%
pedestrians	5 to 10	2 to 5 mins	0 to 4	0 - 100%
picnicking groups	5 to 10	1 to 3 hrs	10 to 50	0%

Table 9.1: User Group Overlap

10. Climbing Contexts

a. We need to derive the degree of exposure to harm for the various people within the domain defined in sect. 9.c. To do this we formally enumerate four actors selected from the groups in Table 10.1 as those carrying significant exposure to harm.

actor	**description**	**group(s)**
A1	active climber	climbers
A2	belayer	climbers
A3	bystander	climbers
A4	spectator	pedestrians may leave the path to wander into the region of concern, and are more likely to linger as spectators than other groups

Table 10.1: Table of Actors

b. For the purposes of analysis we divide the activity of climbing into three contexts where one of those contexts has two sub-modes. This formalism allows us to link activity, and thus exposure to harm, to the physical infrastructure in play.

context	**description**	**infrastructure in play**
C1	*leading* – leader moves up climb clipping bolts as he/she proceeds - belayer belays from the ground	1 to 6 bolts between the bottom and the top of the climb
C2	*lowering-off* – leader is lowered down the climb from the anchor by the belayer –leader may remove quick-draws as he/she goes	the anchor and for a limited time some of the bolts
C3	*top-roping* – climber moves up the climb protected by the rope running through the anchor and belayed by the belayer on the ground	the anchor

Table 10.2: Table of Contexts

mode	**description**
M1	*working* – a style of leading where the leader is challenged by a climb at or beyond his/her capability – for the C1 context duration the leader is certain to fall a number of times
M2	*cruising* – a style of leading where the leader is not strongly challenged by the climb, and a fall during the context duration is unlikely.

Table 10.3: Table of Lead Climbing Modes

c. The typical sequence of activity is as follows -

   i. *Context C1 starts -*
   ii. The leader ties into the rope and the belayer connects the rope to the belay device attached to his/her harness.
   iii. The leader climbs up the cliff fitting a quick-draw at every bolt as it is encountered. The rope is threaded through the quick-draw so it is possible for the leader to continue upwards. The rope acts to limit the extent of the fall should he/she slip.
   iv. The leader does not place body weight on the bolts, quick-draw or rope. They are there simply as a safety system should he/she slip.
   v. When he/she reaches the anchor, he/she clips it and rests his/her body weight on the safety system. The main element bearing any load is the anchor.
   vi. *Context changes to C2 -*
   vii. The climber is then lowered down by the belayer. It is likely he/she will collect the quick-draws placed during the ascent.
   viii. If the quick-draws are removed, then at some point around two-thirds height, the security of the safety system is solely dependent upon the anchor.
   ix. *Context changes to C3 -*
   x. Once down, another person may tie into the rope hanging down from the anchor, and climb with the rope supporting them from

above should they slip. They are belayed by another at ground level. This is called top-roping.

xi. In top-roping, the security of the safety system is solely dependent upon the anchor.

11. Analysis of the Severity of Harm

The severity of harm arising from the realization of a hazard will be classified by a four-category scheme as shown below.

classification	description
S0	No harm.
S1	Minor injury not requiring hospitalisation.
S2	Major injury requiring hospitalisation, but not life threatening or leading to major permanent disability.
S3	Death, or major injury culminating in death, or major permanent disability.

Table 11.1: Classification of Severity of Harm

The KPN domain, compared with other rock climbing domains, has a number of unique features that ameliorate the severity of outcome for many climbing accidents.

- The CBD location, and the road access to the cliff base, guarantees rapid access to medical facilities.
- The base of the cliff, being parkland, provides a far less hazardous impact zone than that typical of most rock climbing crags.

12. Analysis of Hazards

Without restricting the scope of the analysis, it can be seen that there are two broad classes of hazard -

- **Climber fall** – the climber operating in context C1, inevitably will fall as part of the "game", but should never fall under contexts C2 and C3.
- **Rock fall** – the climber could pull a piece of rock from the cliff face. This is an unlikely event for a stabilised cliff face like KPN; nevertheless it will occur from time to time. Rock-fall caused by the movement of people at the cliff top is ruled out because of the cliff-top access restrictions that will be in place.

When a climber falls, his/her safe arrest is subject to correct operation of the rope system. We can categorize a fall depending upon what happens within the safety system.

- **No Failure** – sport climbing nearly always involves "safe" falls. Such falls are safe because the rope system is designed to safely arrest the fall.
- **Methodological Failure** – the climber's fall is not arrested because of a failure on the part of the climber or belayer to observe normal safe climbing practice, eg failure to tie-in to the rope correctly.

- **Infrastructural Failure** - the climber's fall is not arrested because of a failure on the part of the cliff infrastructure, eg a bolt failure

Of course, there is the possibility that a link in the climber's safety system of rope, climber's harness, belayer's harness, belay device and carabiners could fail. However, because such items are all being loaded well within their design limits, equipment failure is almost unknown within sport climbing. Such failures as do occur nearly always come down to a realization of methodological failure.

By considering the above we can construct a formal table of hazards as below

Hazard ID	**Event**	**Context**	**Fall Arrest Failure**	**Description of Harm**	**Recipient of Harm**	**Severity of Harm**
H1	climber fall	C1	none	low energy impact with cliff face or ledge	A1	S0, S1
H2	climber fall	C1, C2, C3	methodological	high energy impact with ground or person on the ground	A1, A2, A3, A4	S1, S2, S3
H3	climber fall	C1, C2, C3	infrastructural	high energy impact with ground or person on the ground	A1, A2, A3, A4	S1, S2, S3
H4	rock fall	C1, C2, C3	n/a	person on the ground struck on the head	A2, A3, A4	S1, S2, S3

Table 12.1: Table of Hazards

13. Estimation of Risk

a. Scope

There are numerous risks associated with recreational climbing. The majority of these are under the control of the climber. This analysis does not consider climber expertise, and the risks that come with inexperience. Instead, this analysis concentrates solely on the hazards associated with the failure of cliff infrastructural components, and serves as one part of the duty of care of any party that installs and maintains such infrastructure.

Thus this analysis will consider only those hazards in which the fixed infrastructure of the cliff can be said to play a part, ie hazard H3 in the *Table 12.1* above. Casual inspection of the problem indicates that the preponderance of risk will be associated with those events whereby the minor hazard H1 (the one normally residual to the sport) is escalated to H3 by bolt failure.

b. The approach taken

From a formal, functional safety viewpoint, the roped system used by sport climbers can be classified as a 'safety function' in that the rope system is not a functional part of the act of climbing (climbers do not ascend by pulling on the rope or the infrastructural elements), but the infrastructure exists purely for the purpose of constraining the hazard H1 should it be realized. The only meaningful measure of the performance of a safety function is the so called safety integrity level, or security level, which is measured as the probability of a specified safety function failing to carry out its function on demand. Thus the ultimate design aim of the risk analysis process is to arrive at acceptable target values for the probability of failure on demand for each class of infrastructural item within the domain. We accept this approach is not entirely valid for the way in which anchors may be used, but believe that, on balance, it provides a superior estimate of risk than other non-quantitative methods.

It should be noted that the above approach differs from other forms of safety assessment, for example, the situation where the safety of a structure which is loaded as part of its normal function needs to be assessed. Here we deal with concepts like 'safe working loads" which are set at a point below ultimate failure loads according to quite different considerations. This type of "safety margin" is different to that applied to a safety function. Using modern functional safety concepts, which are now well established in systems engineering, the approach taken should be probabilistic and quantitative.

The steps taken will be as follows -

- Derive the exposure to H3, as modulated by contexts C1, C2 and C3, and then attribute those exposures to specific items or categories of items of infrastructure through assumptions about typical climb bolting patterns. The output of this stage is a set of exposure figures expressed as proportions of context duration for each item of infrastructure.
- Derive demand rates in terms of demands per context duration from exposure figures through assumptions about climber behaviour. The output of this stage is a set of demand rates for each item of infrastructure.
- Derive temporal demand rates (demands per annum) for each item of infrastructure based on assumptions about climber behaviour, and likely future climbing traffic levels for KPN.
- Propose an acceptable rate of occurrence of harm for each of S1, S2 and S3, and use this to drive a probability of failure on demand target (PFD) for each item of infrastructure.

The process is illustrated in *Fig.2*.

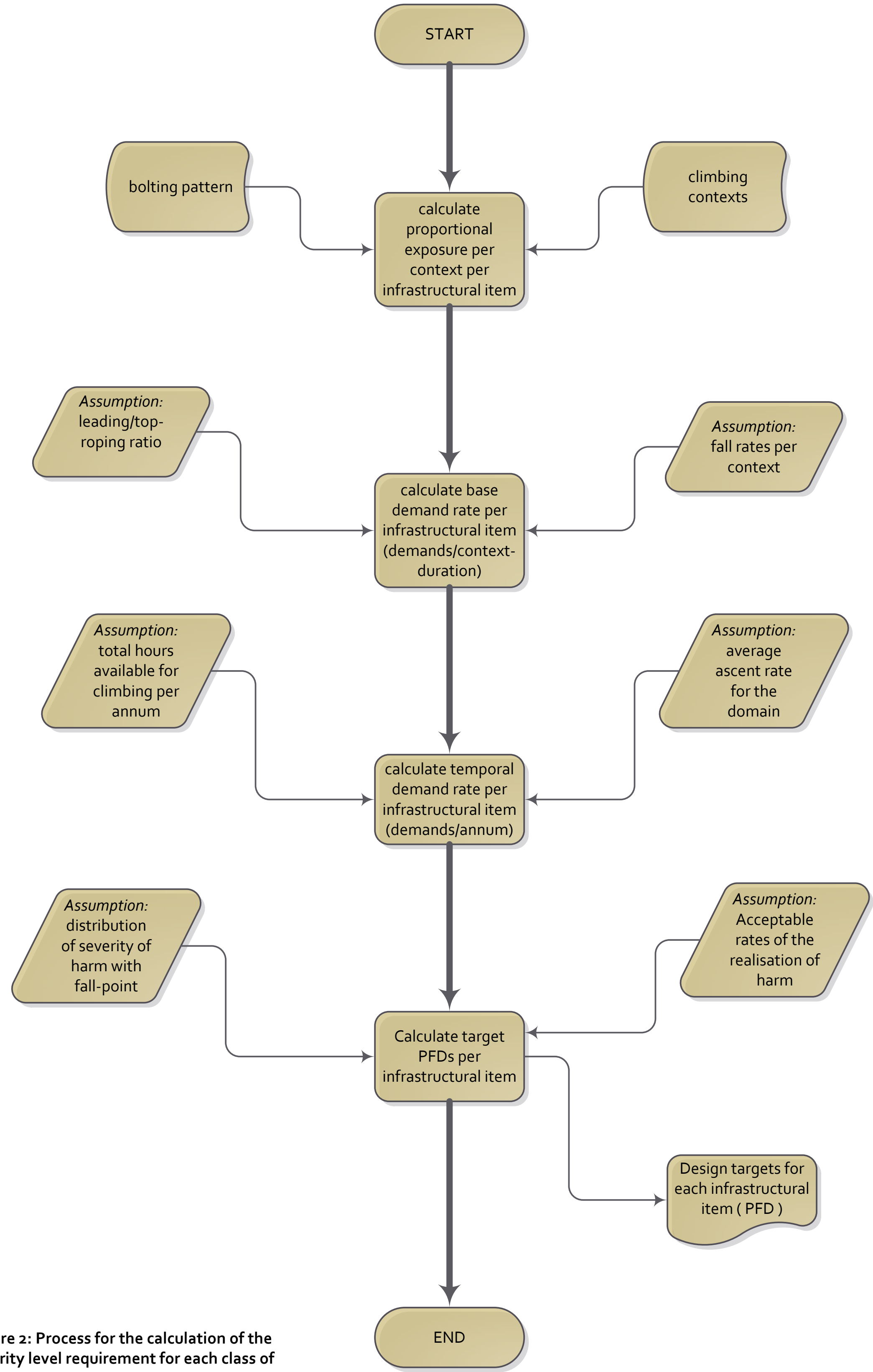


Figure 2: Process for the calculation of the security level requirement for each class of item of infrastructure

c. Calculating the exposure to H3

Analysis of the hazard H3 according to context allows us to estimate exposure to hazard as a proportion of the context duration as follows –

i. **Context C1** – A bolting pattern likely to be used at KPN is 6 equally spaced bolts between the anchor and the ground. The peculiarities of each climb will mean that there will be variations in this pattern. However across the 30 or so climbs proposed, this pattern is likely to be a good assumption for calculation of exposure. Thus we can break the duration of C1 into 7 equal segments, and estimate exposure in 1/7th or 0.14 increments.

   Until the leader clips the first bolt there is no exposure to H3. Once the first bolt is clipped there is an exposure associated with bolt-1 until bolt-2 is clipped. From then on, the exposure is associated with bolt-2, until bolt-3 is clipped. Once bolt-3 and successively higher bolts are clipped, the climber is sufficiently high off the ground that it would take a double bolt failure (ie bolt-3 and bolt-2) for H3 to be realized, and given the low probability of such an event, an exposure of 0 is attributed to bolts 3, 4, 5 and 6 and the anchor.

   Thus we assign an exposure of 0.14 to first bolts and 0.14 to second bolts, and 0 to all others.

ii. **Context C2** – When a leader is lowered off a climb by threading the anchor, if he does not remove the quick-draws as he is lowered, then, given the rope also threads the top and the lower bolts, the exposure to anchor failure is negligible. The top, and some of the lower bolts, would need to simultaneously fail along with the anchor in order that H3 be realized. However, if the leader does remove quick draws on the way down, at the two-thirds point exposure to H3 associated with anchor failure becomes real. We will assume this latter worst-case condition and apply an exposure of 0.67 to the anchor for C2.

iii. **Context C3** – When a climber is being top-roped through the anchors, the exposure to anchor failure applies for the entire climb. It could be argued that the harm ensuing from a failure when the climber is very low on the climb is unlikely to realize H3. However, given that we are permitting S1 as a possible H3 outcome, we will err on the conservative side, and set exposure associated with the anchor for C3 to be 1.0.

The output of the above analysis can be summarised as per the *Table 13.1* below. Exposure figures are in terms of a proportion of the corresponding context duration.

Table 13.1: Exposure to H3 classified by context and infrastructural element

context	**bolt-1**	**bolt-2**	**bolt-3**	**bolt-4**	**bolt-5**	**bolt-6**	**anchor**
C1	0.14	0.14	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00	0.67
C3	0.00	0.00	0.00	0.00	0.00	0.00	1.00

d. Calculating base demand rates on infrastructure

For the moment let's assume that C1 is the only context that is challenging the infrastructure, then the demand rate for say, bolt-1, is the C1 fall rate (in falls per context duration) times the C1 exposure for bolt-1. In other words, if a lead climber invariably falls once on making his way to the anchor (ie he falls off and gets back on to continue from the point at which he fell) then the demand rate for bolt-1 will be 1.0 x 0.14 according to the exposure table above, ie on average, he will load bolt-1 only once every seven ascents. Note that here we are assuming that the climber is equally likely to fall at any point on the ascent. This assumption is discussed further in the footnote[1]

In reality, the infrastructure will see demands coming from all three contexts. . If we take any one climb, and consider the climbing activities that occur there, both lead climbing and top-rope climbing will occur. Lead climbing involves context C1 followed by C2, while top-roping involves just context C3. The base demand rate will need to reflect the proportion of each type.

On the foregoing basis we can write the following equation –

Equation 1: base demand rate

$$R_i = P_{lead}(F^{C1} \bullet E_i^{C1} + F^{C2} \bullet E_i^{C2}) + P_{tr}(F^{C3} \bullet E_i^{C3})$$

R_i is the base demand rate for the *i*th infrastructural element, ie bolt-1 to bolt-6, anchor
P_{lead} is the proportion of ascents that are lead within the domain
P_{tr} is the proportion of ascents that are top-roped within the domain
E_i^{C1} is the exposure of the *i*th infrastructural element under context *C1*
E_i^{C2} is the exposure of the *i*th infrastructural element under context *C2*
E_i^{C3} is the exposure of the *i*th infrastructural element under context *C3*

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[1] The assumption that the climber is equally likely to fall at any point on a climb is easily challenged. All climbs have a "crux", where the fall is most likely, and thus have a particular bolt that is most often the subject of a demand. However, for a climber very familiar with a climb, this assumption of necessarily falling at the "crux" need not be correct. A complacent climber often falls when he least expects to. Thus, an easy climb where the majority of climbers are well within their capabilities won't necessarily see a disproportionate number of demands on the crux bolt. For a harder climb, the situation will be different.

Furthermore, for a climbing area with a reasonable number of climbs, as we have at KPN, there is no reason to believe that the "crux" will always be at a set location with respect to bolt number. Thus in assessing the risk for the overall domain, there is no reason to believe that the high exposure bolts 1 and 2 will necessarily be challenged any more than the average bolt. The reverse situation is just as likely to true

F^{C1} is the fall rate for the domain under context *C1*
F^{C2} is the fall rate for the domain under context *C2*
F^{C3} is the fall rate for the domain under context *C3*

In order that we can arrive at P_{lead} and P_{tr} above, we need to make assumptions about the behaviour of the climbing population and the proportion of people lead climbing and/or top-roping. Two sets of figures are used. The first being an estimate derived from observation of current behaviour at the existing Kangaroo Point Cliffs, and the second being a "stress" input which will be used to test the sensitivity of the overall analysis to its input assumptions. This figure is derived from speculation that the current European practice of discouraging top-roping will make its way into the Australian climbing scene resulting in a preponderance of lead climbing ascents. These assumptions are tabulated as *Assumption Set 1* below.

Assumption Set 1: relative proportions of ascents by leading and top-roping

type	P_{lead}	P_{tr}	**comment**	
primary	0.50	0.50	current behaviour	
stressed	0.80	0.20	possible future behaviour	

The next figures, which we will need, are the fall rates for each context. Those for C2 and C3 are relatively easy to get at, as follows. The leader, having climbed under C1, always lowers-off under C2 and consequentially, under C2, always weights the anchor. This gives a fall rate of 1 fall per context duration for C2. Similarly, a top-roper will always be lowered-off when they have finished a climb. Beyond this one "fall", there is the additional possibility that they may have "sat-back" and weighted the anchor several times during the ascent. On this basis we can associate an average fall rate of something like 1 + 2 to C3.

The fall rate for the C1 context is more difficult to estimate. As indicated under *Table 10.3* we can usefully divide leading climbing into two modes, M1 and M2. One of these, M1, generates a much higher fall rate than the other. In the case of a climbing area like Kangaroo Point where climbs are not only highly accessible, but also relatively easy, we find that most people are climbing routes that they have done many times before, and M2 is the dominant mode with lead falls being relatively rare. This contrasts with a hard climbing destination like Mt Coolum, for instance. Here the majority of climbers are challenged by the difficulty, the mode is distinctly M1, and climbers will fall many times in the course of one attempt on a route. Thus, in estimating the fall rate for the context, C1, we need to apportion ascents between M1 and M2, before deriving an overall estimate for $F^{C1,}$ as shown in *Assumption Set 2a* below.

Assumption Set 2a: context C1 fall rates (primary)

mode	**falls/context duration**	**proportion of ascents**	F^{C1}	
M1	5.00	0.20	1.00	
M2	0.10	0.80	0.08	
combined		**1.00**	**1.08**	

It is useful to construct a “stressed” version of *Assumption set 2a.* At first sight it might seem that the proportion of M1 mode climbing will increase over the years, however, there are reasons to believe the proportion will actually decrease as younger, stronger climbers enter the sport. As the climbing population becomes stronger, it is to be expected that the majority will not be challenged by the grades of climbs likely to be encountered at KPN. This trend is reflected in *Assumption Set 2b* below.

Assumption Set 2b: context C1 fall rates (stressed)				
mode	**falls/context duration**	**proportion of ascents**	F^{C1}	
M1	5.00	0.10	0.5	
M2	0.10	0.90	0.09	
combined		**1.00**	**0.59**	

Taking the overall values for F^{C1} arrived at above, we can add in the other fall values to build the summary *Table 13.2* below.

Table 13.2: fall rates for each context			
type	F^{C1}	F^{C2}	F^{C3}
primary	1.08	1.00	3.00
stressed	0.59	1.00	5.00

We now have all the inputs, *P*, *F* and *E* needed to calculate the base demand rate per infrastructural element as per *Equation 1* above. *Table 13.3* summarises the results.

Table 13.3: base demand rate per item of infrastructure (demands/context-duration/item)							
type	R_1	R_2	R_3	R_4	R_5	R_6	R_{anchor}
primary	0.076	0.076	0.000	0.000	0.000	0.000	1.835
stressed	0.066	0.066	0.000	0.000	0.000	0.000	1.536

It can be seen that only Bolt-1, Bolt-2 and the anchor are subjected to demands that could realize hazard H3. Also it can be seen that the demand rate on the anchor far exceeds that on the first two bolts.

e. Calculating Temporal Demand Rates on Infrastructure

In section 13d above, after due consideration of the contexts associated with lead climbing and top-roping ascents, and the relative proportions of those two types of climbing, we estimated the average demand rate on each infrastructural element in terms of demands per context duration. This equates to the demand rate per ascent, averaged over all climbing styles likely to be conducted within the domain. Thus if we estimate the likely number of ascents per annum at KPN regardless of style, then we can transform the data of *Table 13.3* into the more useful temporal demand rate, ie the demands per annum per infrastructural element. This relationship is formally described in *Equation 2* below.

Equation 2: temporal demand rate

$$\Delta_i \;=\; R_i \bullet 1/t^c \bullet T_{av} \bullet N \bullet U_{av}/100$$

where –

Δ_i is the temporal demand rate for the *i*th infrastructural element, ie bolt-1 to bolt-6, anchor in demands per annum
R_i is the base demand rate for the *i*th infrastructural element in demands per context duration
t^c is the average context duration in hours
T_{av} is the number of climbing hours available per annum
N is the number of routes proposed for development at KPN
U_{av} is the average percentage utilization of the domain

Firstly, we estimate the total number of hours available for climbing, T_{av}. In Brisbane, high summer temperatures and humidity make climbing almost impossible during the middle of the day, and we adjust the hours available accordingly. In addition, climbing by artificial light during the evening is very popular at Kangaroo Point, and we have added availability to reflect this.

AssumptionSet 3: total hours available for climbing per annum						
hot season				**cool season**		
start month	**end month**	**total weeks**		**start month**	**end month**	**total weeks**
11	3	21.67		4	10	30.33
period	daily hours	total hours		period	daily hours	total hours
morning	4	607		morning	6	1274
afternoon	2	303		afternoon	6	1274
evening	3	455		evening	3	637
hot season total		1365		**cool season total**		3185
annual total		**4550**				

Secondly, we can attribute a minimum value to the time taken for a typical ascent, t^c, given the physical limitations of performing such an endeavour. Also, we can reliably estimate the number of climbs proposed for the domain, N, and thus use these two figures to put an upper limit on the total number of ascents per hour for the domain.

Thirdly, we need to consider, U_{av}, the percentage utilization of the domain. Considering the fact that, not all climbs are going to be equally popular, and there won’t be people queuing continuously to get on a climb, in reality, the actual ascent rate will be very much less that the maximum possible. However, we can anticipate that usage rates will soar over the next twenty years, and prudent design practice dictates that a “stressed” ascent rate near the maximum physical capacity of the domain should be applied. These assumptions are tabulated below.

Assumption Set 4: overall ascent rate for the domain

type	avg context period (mins)	number of routes	utilization (%)	ascent rate (ascents/hr)
primary	20.00	30	2.00	1.80
stressed	20.00	30	80.00	72.00

Given that we now have estimates of the total climbing hours likely to be available, along with estimates of the likely overall ascent rate, we can transform the base demand rates of *Table 13.3* to temporal demand rates as shown in *Table 13.4* below.

Table 13.4: temporal demand rate per item of infrastructure (demands/annum/item)

type	R_1	R_2	R_3	R_4	R_5	R_6	R_{anchor}
primary	619	619	0	0	0	0	15,029
stressed	24,767	24,767	0	0	0	0	601,146

The table shows that the effect of “stressing” input assumptions to reflect possible future scenarios is dramatic, and it is clear that the trivial assumption, namely, *that which has worked without mishap in the past, will necessarily do so in the future* is an approach fraught with danger. Whilst it could well be that bolting practices as they have existed over the past years would offer sufficient margin of safety to accommodate the projected increase in the demand without surfacing an unacceptably serious injury rate, it is equally possible they may not. The truth is we don’t know, and this consideration is the driving reason for the probabilistic approach that we have taken in this analysis.

f. Calculating the Target PFDs

Given that we now have estimates of the annual demand rate per item of infrastructure, we can apply a probability of failure on demand, *PFD*, to arrive at the annual rate of realisation of H3. Then, making further assumptions about the proportion of severity of harm arising from such a realisation, we can further deduce the incidence rates of S0, S1, S2 and S3 per annum.

Assumption Set 5, below, takes a fairly conservative view of the outcome of a typical ground-fall. There are no solid data to drive these assumptions, given the sporadic reporting of the serious accidents that do occur at Kangaroo Point Cliffs, and there is no reporting at all for those cases where people walk away unharmed.

However, we do know that there is a big difference in outcome when a person falls from the top of the cliff, compared with at a point close to the base. Given that infrastructural elements are distributed up the height of the cliff, then, if we are to associate severity of harm with specific infrastructural items, it is necessary to consider the height from which a climber might fall should a specific item of infrastructure fail on demand. Thus in *Assumption Set 5* it will be seen that we have divided the cliff into four zones based on height, and then made an assumption as to the distribution of severity of harm attributable to a fall from that zone.

Assumption Set 5: distribution of severity of harm with fall point

fall point	***S0***	***S1***	***S2***	***S3***
upper	0.00	0.05	0.25	0.70
mid-upper	0.05	0.15	0.35	0.45
mid-lower	0.10	0.45	0.35	0.10
lower	0.50	0.30	0.15	0.05

Next, we can consider the likely fall point should an item of infrastructure fail on demand. Failure of say bolt-1 is likely to result in a ground fall from no higher than the second bolt, and, based on our earlier assumptions that there will be 6 bolts evenly distributed over the height of the climb, it is evident that bolt-1 failures will be associated with falls from the lower quarter of the cliff. Analogous reasoning can be applied to the other bolts. For the anchor, however, failure could drop the climber from any point in the climb, and the distribution of the severity of harm is taken as an average of all four of the fall points. *Table 13.5* summarises these considerations.

Table 13.5: distribtution of severity of harm associated with infrastructure type

	bolt-1	**bolt-2**	**bolt-3**	**bolt-4**	**bolt-5**	**bolt-6**	**anchor**
S0	0.50	0.10	0.05	0.05	0.00	0.00	0.16
S1	0.30	0.45	0.15	0.15	0.05	0.05	0.24
S2	0.15	0.35	0.35	0.35	0.25	0.25	0.28
S3	0.05	0.10	0.45	0.45	0.70	0.70	0.33

We are now in a position to estimate the annual rate of realisation of harm that a specific item of infrastructure attracts.

Equation 3: annual rate of realisation of harm

$$I_i^S = \Delta_i \bullet PFD_i \bullet P_i^S$$

where –

I_i^S is the annual incidence of harm of severity *S* attracted by the *i*th infrastructural element.

Δ_i is the temporal demand rate for the *i*th infrastructural element, ie bolt-1 to bolt-6, anchor in demands per annum.

PFD_i is the probability of failure on demand associated with the *i*th infrastructural element.

P_i^S is the probability of severity of harm *S* associated with the *i*th infrastructural element, as itemised in *Table 13.5*

In practice, what we would normally be seeking is the PFD_i necessary to reduce the value of I_i^S to an acceptable level. That is, we want to ensure that the annual rate of realisation of harm does not exceed some notional, but socially acceptable value, and to calculate the PFD required to achieve the same. Thus a more useful form of Equation 3 is to re-arrange it as follows.

Equation 4: target PFD

$$PFD_i^S = I_i^S / (\Delta_i \bullet P_i^S)$$

where –

PFD_i^S is the target PFD for infrastructural element *i*, derived from the desired limit, I_i^S, on the rate of realisation of harm, of severity *S,* for same infrastructural element *i*.

Setting the limits for the socially acceptable value for the annual rate of realisation of harm is a somewhat arbitrary process. However, it is possible to work broadly within orders of magnitude. For example, a fatality every year is unlikely to be deemed acceptable because one event is easily within memory of the last. A fatality every 10 years, however, is not likely to build this way in the public perception. A fatality every 100 years is super-generational and is indistinguishable from a zero accident rate.

Based on the above reasoning we have applied annual rate of < 0.1 incidents p.a. to the severity classes S3, five times that for S2, and for the less serious incidents applied a notional factor of tenfold per reducing severity class.

The target PFDs required to constrain the realisation of harm within the limits set above are shown below for both the “normal” and the “stressed” cases.

Table 13.6: acceptable rates of the realisation of harm and corresponding PFD targets (normal)

	acceptable rate of realisation of harm (p.a.)	PFD_1^S	PFD_2^S	PFD_3^S	PFD_4^S	PFD_5^S	PFD_6^S	PFD_{anchor}^S
S0	10	3.2E-02	1.6E-01					4.1E-03
S1	1	5.4E-03	3.6E-03					2.8E-04
S2	0.5	5.4E-03	2.3E-03					1.2E-04
S3	0.1	3.2E-03	1.6E-03					2.0E-05

Table 13.7: acceptable rates of the realisation of harm and corresponding PFD targets (stressed)

	acceptable rate of realisation of harm (p.a.)	PFD_1^S	PFD_2^S	PFD_3^S	PFD_4^S	PFD_5^S	PFD_6^S	PFD_{anchor}^S
S0	10	8.1E-04	4.0E-03					1.0E-04
S1	1	1.3E-04	9.0E-05					7.0E-06
S2	0.5	1.3E-04	5.8E-05					3.0E-06
S3	0.1	4.0E-06	4.0E-05					5.1E-07

g. Conclusions

- By meeting the safety integrity requirements for S3, we also meet the requirements for S0, S1 and S2.
- The most stringent requirements for security are the anchors, by an order of magnitude or more

- The potential for future trends in recreational climbing to elevate the required security is marked. It would be wise to design-in an extra two orders of magnitude of security for future developments.
- Thus we can summarise -

All bolts must provide a PFD of less than 4 in 10^6

All anchors must provide a PFD of less than 5 in 10^7

14. A Probabilistic Model for the Demand

a. The approach taken

When a climber falls, a load is placed on the bolt responsible for arresting the fall. This load starts from zero and rapidly moves through to a relatively high value as his/her body weight is decelerated by the internal workings of the rope, before falling back to a value equal to twice the climber's weight. This load demand unfolds rapidly, typically in a period of less than one second.

A modern climbing rope is designed to absorb the energy of a fall partly by elastic deformation and partly by frictional loss as the internal strands of the rope work across one another. Unlike the behaviour of a normal rope, the frictional loss is large and there is very little elastic rebound when a fall is arrested.

The figure below shows the behaviour of a typical dynamic climbing rope. Note that the energy of the fall is dissipated within two rebound cycles. Note also that the system displays almost linear extension with load. It should be understood that much of this response is attributable to distributed viscous damping within the rope itself, and the actual spring constant of the rope measured under static conditions will be quite different.

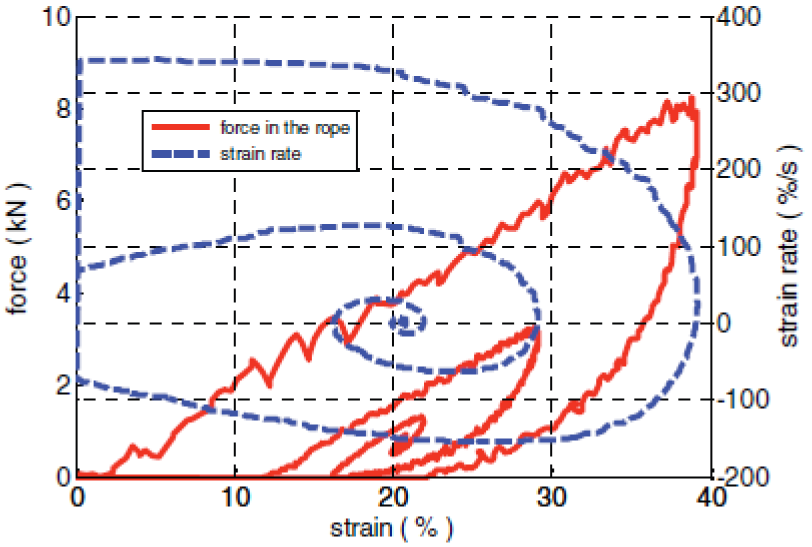

Figure 3: Behaviour of dynamic climbing rope arresting a fall. From Bedogni and Manes 2011[2]

Because the oscillation is strongly damped, the first maximum dominates the development of load over time, and therefore can be considered the component of load responsible for bolt failure. It is reasonable, therefore, to simplify the analysis by comparing just the peak force resulting from a fall against the ultimate strength of the bolt. Thus if the peak force exceeds the ultimate strength of the bolt, we will assume that the outcome is a failure on demand.

It is possible to construct a simple, elastic deformation model, and feed into it the various parameters, such as climber weight and fall factor which will yield the peak force on the arresting bolt. When the parameters are fed in as their probability distributions, we obtain the probability distribution for the peak force on the arresting bolt.

Finally, knowing we require a PFD of, say 1 in 10^6, we can look up the resultant distribution to find the bolt strength required to ensure that less than 1 in 10^6 falls will exceed it. Thus we now have a means of relating a desired safety integrity level to the bolt strength required to achieve that level.

b. The model

Over the years, a number of physical models have been proposed based on a simple consideration of energy conservation. A modern reworking of the maths to include the effect of the frictional loss at the arresting carabiner is given by Jay Tanzman 2009[3].

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[2] Bedogni, V and Manes, A (2011). A constitutive equation for the behaviour of a mountaineering rope under stretching during a climber's fall. Procedia Engineering **10** (2011) 3353–3358

[3] Tanzman, J (2009). Incorporating Friction into the Standard Equation for Impact Force. Retrieved June 14th, 2013, from http://jt512.dyndns.org/impact-force-rev1.pdf

Attempts to incorporate viscous damping, such as Pavier M 1998[4], whilst claiming accurate simulations, are in our opinion, of dubious generality due to lack of physicality.

Bedogni and Manes 2011[5] have avoided the complexity by proposing a parametric model based on a fitted function for each of strain, strain rate and strain recovery rate. The development of this model is computationally intensive.

For our purposes, we need to have a model that can be iterated millions of times to build up the required probability distribution for the impact force. For this reason, we have settled on a simple elastic model. Extensive drop tower tests have shown that the "apparent spring constant" of a dynamic rope, illustrated in Fig 3 above, is constant over a realistic range of drop weights and fall factors. For example, see the data set presented by rope manufacturers, PMI[6]. Thus all we need do is calculate the "apparent spring constant" from the manufacturer's drop tests, and proceed with a solution using Tanzman's equation.

The basic equations used by the model are -

$$T_1 = w + \sqrt{w^2 + \frac{4krw}{2 + (r-2)\mu}}$$

where -

$T_1 is\ peak\ climberside\ tension$ (N)
$w\ is\ the\ climber's\ weight\ (N)$
$k\ is\ the\ modulus\ of\ the\ rope\ (N)$
$r\ is\ the\ fall\ factor$
$\mu\ is\ the\ fraction\ of\ climberside\ tension\ opposed\ by\ friction\ at\ the\ carabiner$

and -

$$T_2 = (1-\mu)T_1$$

where-

$T_2\ is\ the\ peak\ belayerside\ tension\ (N)$
$T_1\ is\ peak\ climberside\ tension\ (N)$
$\mu\ is\ the\ fraction\ of\ climberside\ tension\ opposed\ by\ friction\ at\ the\ carabiner$

and finally -

$$F = T_1(2-\mu)$$

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[4] Pavier, M (1998). Experimental and theoretical simulations of climbing falls. Sports Engineering (1998) **1** 79-91

[5] Bedogni, V and Manes, A (2011). A constitutive equation for the behaviour of a mountaineering rope under stretching during a climber's fall. Procedia Engineering **10** (2011) 3353–3358

[6] "What heavy climbers need to know". Pidgeon Mountain Industries Inc 1999. Retrieved April 2nd 2014, fromhttp://www.safeclimbing.org/education/Heavy_Climbers_Beware.pdf

where -

F is the force on the arresting bolt (N)
T_1 is peak climberside tension (N)
μ is the fraction of climberside tension opposed by friction at the carabiner

c. The inputs to the model

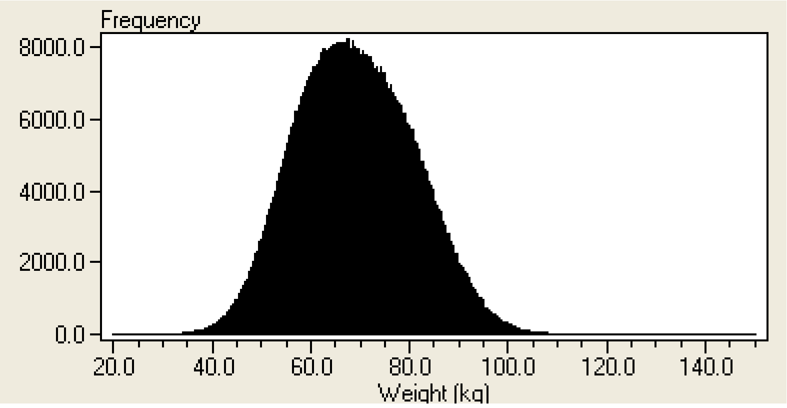
i. Climbers weight

For each iteration of the model, a climber is selected from a population of 300 male and 200 female climbers. The climber selected is assumed to have a weight derived from a population as characterised in the table below.

	mean (kg)	sd (kg)
male	75	10
female	60	8

Table 14.1: Table of Inputs - weight

The output of the weight generation algorithm for the above inputs is illustrated below.



The statistics for the upper tail of the distribution are -
1 in 10,000 exceeds 110.74 kg
1 in 1,000 exceeds 104.24 kg
1 in 100 exceeds 95.92 kg

ii. Modulus of rope

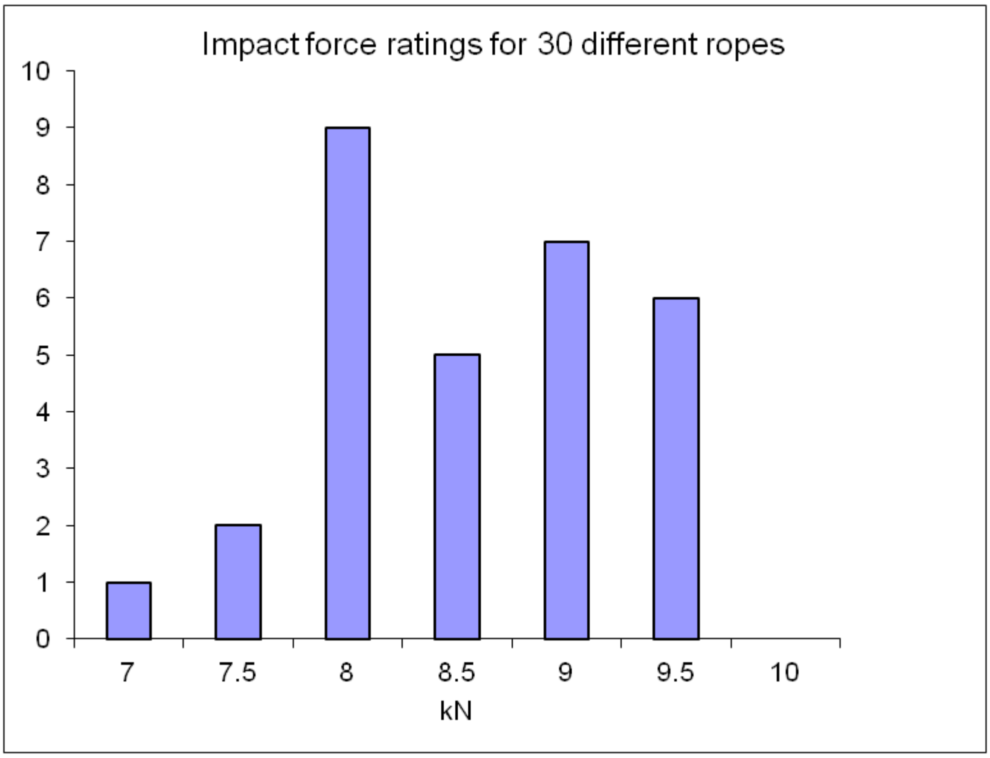
There are a limited number of manufacturers of dynamic climbing ropes, and all of these manufacture in compliance with the UIAA 101 / EN892 standard. This fact allows us to set limits on the modulus of any rope likely to be employed within the domain.

Manufacturers publish the UIAA 101 test figure they obtain for every rope they market. A representative sample of climbing rope data is provided in the table below.

manufacturer	model	dia	impact force (kN)
BlueWater	Eliminator	10.2	8
Petzl	Zephyr	10.3	7.3
BlueWater	Pulse	9.9	7.8
Mammut	Galaxy	10	9.2
Mammut	Flash	10.5	9
Mammut	Flex	11	9
Mammut	Supersafe	10.2	8.8
Sterling	Evolution	9.8	8.8
BlueWater	Accelerator	10.5	8
Mammut	Superflash	10.5	9.2
Mammut	Serenity	8.9	9.5
Mammut	Infinity	9.5	9.1
Sterling	Marathon	10.1	8.6
Petzl	Fuse	9.4	8.3
Sterling	Fusion Nano	9.2	8.4
Mammut	Revelation	9.2	9.3
Petzl	Xion	10.1	8.2
Edelrid	Eagle	9.8	9.4
Edelrid	Harrier	10	9
Edelweiss	Axis II	10.2	8
Edelweiss	Energy	9.5	7.8
Tendon	Ambition	10.2	8
Tendon	Ambition	10.5	8.5
Tendon	Ambition	10	7.2
Tendon	Ambition	10.4	8.2
Tendon	Master	9.2	8
Tendon	Master	9.4	7
Tendon	Master	9.7	7.6
Beal	Edlinger	10.2	8
Edelrid	Osprey	10.3	8.9

Table 14.2: Table of Inputs - published impact force

The above data is presented as a histogram in below.



Ropes age through use. In particular, the last 5m at each end change structure such that the end sections become less effective at dissipating the energy of a fall. Normally, climbers combat this deterioration by gradually cutting and discarding the ends of the rope as it ages. Some ropes age faster than others, and some climbers replace their ropes less often than others. Such considerations make it difficult to accurately model the distribution of the rope modulus characteristic likely to be present within the domain. We have chosen to use a rectangular distribution located between the limits of 8 and 10kN.

The model requires the modulus of the rope, not its impact force rating, as an input. Because the rating is derived from a standard test setup, it is possible to convert the quoted impact force to the modulus by applying a variation of the Tanzman equation as follows -

$$k = \frac{U(U - 1.568)}{2.899}$$

where -

$k \text{ is the rope modulus } (kN)$

$U \text{ is the UIAA impact force rating } (kN)$

iii. Fall factor

The fall factor is measured as the ratio of the distance fallen to the amount of active rope in the system. It is a dimensionless quantity which neatly captures the magnification of the forces that will be generated in the system for a given weight of climber, and rating of climbing rope. The potential fall factor changes markedly as the climber proceeds up a climb, and thus we find each item of infrastructure has its own characteristic distribution of fall factors.

From Table 14.1 we see that bolts are associated with context C1, while the anchors are associated with contexts C2 and C3. We will start by analysing what context C1 means for each bolt in turn. This context defines six equally spaced bolts between the ground and the anchors. We will assume a spacing of 3m between bolts, which is fairly typical of a modern sport climb.

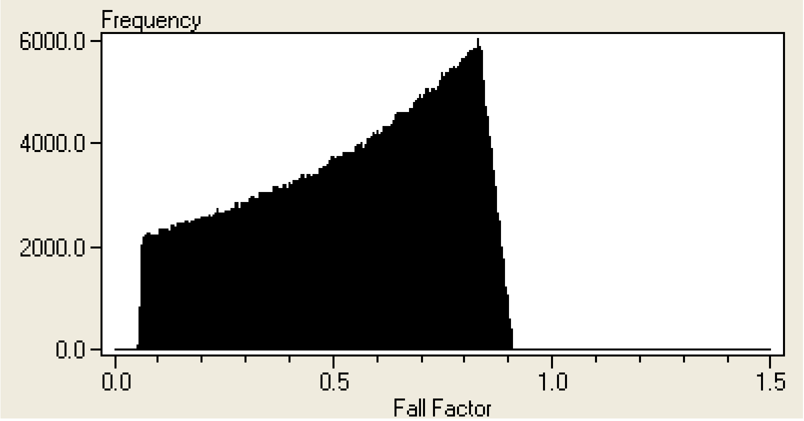
Bolt-1 The climber cannot load the bolt until he/she clips it. Typically this is done when the climber's feet are well below the height of the bolt. Once clipped, and until such point as the climber's waist is above the bolt, any fall will cause no more load than twice body weight to be applied to the bolt, simply because the rope is supporting the climber from above. However, as the climber proceeds upwards the possibility that the climber can fall twice the distance their waist is above the bolt becomes real. This fall distance, as well as the amount of rope in play, increases until they reach up and clip the second bolt. Typically this will occur when their waist is 2m above the lower bolt.

Thus for the fall factor at the first bolt, there is a distribution of possible values depending from where between first and second bolt the climber falls. The inputs to the model are summarised in the table below.

Min. height of 1st bolt (m)	3.0
Max. height of 1st bolt (m)	3.5
Fall Point min. waist height above 1st bolt (m)	0.1
Fall point max. waist height above 1st bolt (m)	2.5

Table 14.1: Table of Inputs - fall factor bolt-1

The output of the fall factor distribution generator for the above inputs is illustrated in the figure below.



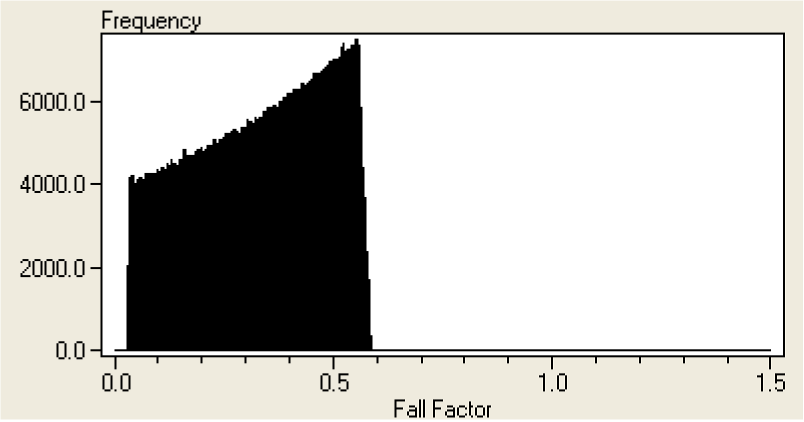
The statistics for the upper tail of the distribution are -
1 in 10,000 exceeds 0.9
1 in 1,000 exceeds 0.897
1 in 100 exceeds 0.876
1 in 10 exceeds 0.816
1 in 2 exceeds 0.567

Bolt-2 Having reached and clipped the second bolt, the climber ascends past it, and a scenario similar to that for the first bolt unfolds except that now there is twice the amount of rope in the system, and the fall severity as measured by the fall factor is diminished. For the second bolt, the following inputs are used.

Min. height of 2nd bolt (m)	6.0
Max. height of 2nd bolt (m)	6.5
Fall Point min. waist height above 2nd bolt (m)	0.1
Fall point max. waist height above 2nd bolt (m)	2.5

Table 14.2: Table of Inputs - fall factor bolt-2

The output of the fall factor distribution generator for the above inputs is illustrated in the figure below.



The statistics for the upper tail of the distribution are -
1 in 10,000 exceeds 0.582
1 in 1,000 exceeds 0.579
1 in 100 exceeds 0.567
1 in 10 exceeds 0.528
1 in 2 exceeds 0.339

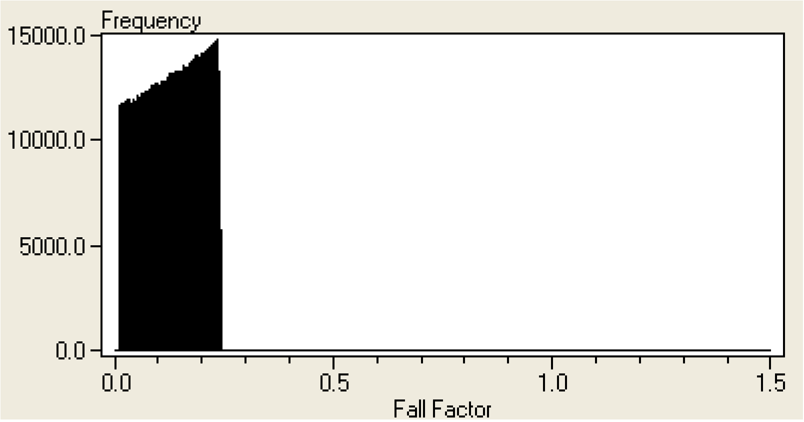
The risk analysis shows that for bolts higher than the second, the exposure to harm from a single point infrastructural failure falls to zero (Table 13.1). However, from a design point of view it is of interest to see what happens to the distribution of fall factors associated with higher bolts. To this end we will examine the case of bolt-6.

Bolt-6 For this bolt the following inputs are used.

Min. height of 6th bolt (m)	18.0
Max. height of 6th bolt (m)	18.5
Fall Point min. waist height above 6th bolt (m)	0.1
Fall point max. waist height above 6th bolt (m)	2.5

Table 14.3: Table of Inputs - fall factor bolt-6

The output of the fall factor distribution generator for the above inputs is illustrated in the figure below.



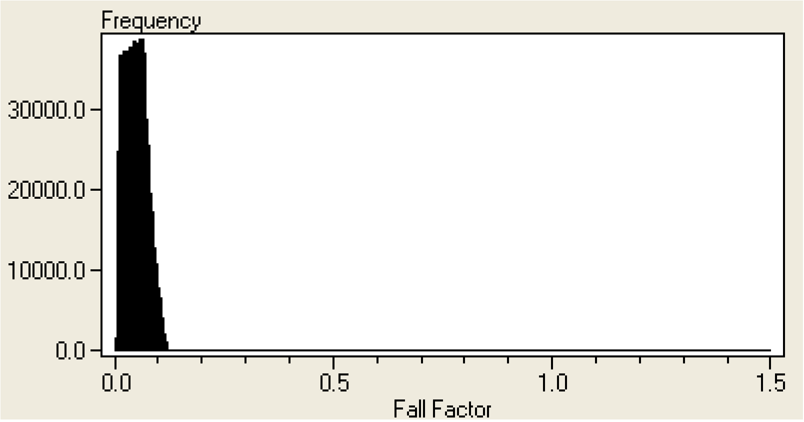
The statistics for the upper tail of the distribution are -
1 in 10,000 exceeds 0.24
1 in 1,000 exceeds 0.237
1 in 100 exceeds 0.234
1 in 10 exceeds 0.216
1 in 2 exceeds 0.129

Anchors Under C2 or C3, the climber will load the anchor as he/she is lowered off the climb. Falls do not normally occur in these contexts, unless, by virtue of extreme inattention on the part of both belayer and climber under C3. Under these circumstances, the climber may fall several metres, but the fall factor is guaranteed to be low due to the fact the rope runs up through the anchor at the top of the cliff. The following inputs were used.

Min. length of active rope (m)	20
Max. length of active rope (m)	38
Min. fall (m)	0.1
Max. fall (m)	2.5

Table 14.4: Table of Inputs - fall factor anchors

The output of the fall factor distribution generator for the above inputs is illustrated in the figure below.



The statistics for the upper tail of the distribution are -
1 in 10,000 exceeds 0.117
1 in 1,000 exceeds 0.114
1 in 100 exceeds 0.105
1 in 10 exceeds 0.078
1 in 2 exceeds 0.042

iv. Frictional Loss

Although we can factor-in the effect of friction over the arresting carabiner in a reasonable manner, it is difficult to arrive at a realistic distribution of frictional loss for a number of reasons.

The proportion of climber-side tension that makes it through to the belayer-side is dependent upon the degree to which the rope wraps the carabiner, the type of carabiner and the finish on the rope. For most situations, the belayer-side sees 50% to 70% of the load of the fall on the climber-side.

If the rope does not run straight to the arresting carabiner, then frictional losses come into play at the intervening carabiners, effectively altering the fall factor, and the impulse load seen by the arresting bolt.

The effect of changing the friction in the system has a non-obvious influence on the shape of the distribution of impact forces at the arresting bolt. By inspection, however, we note that factoring an increase in friction at the arresting carabiner has the effect of restricting the upper tail of the distribution. With this consideration in mind, we have adopted a precautionary approach by setting the frictional loss at 0.2 of climber-side tension, which is somewhat below the notional value of 0.33 commonly used in such analyses.

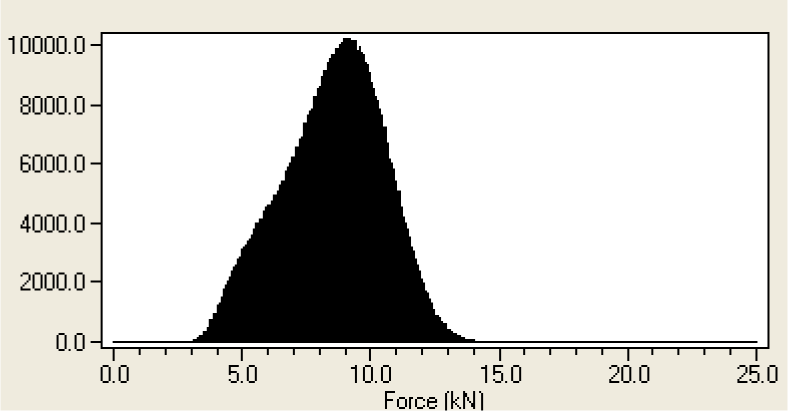
v. Other Factors

The model makes the assumption that there is no slippage or yielding at the belayer-end of the system. In reality, such is rarely the case. Belay devices such as ATC’s always yield to some degree. Furthermore, it has been shown that knots, and the belayer’s harness, are significant sources of give in the system. Over and above this, experienced belayers will jump slightly as they catch a fall, the action of which is to reduce their effective weight as the rope takes up. All of the above increase the distance over which a fall is arrested, and work to reduce the impact force on the arresting bolt. Thus, we can see that the model will be delivering figures biased towards the worst case. In turn, this means that our estimate of impact force for a required PFD will over rather than under estimate.

d. The outputs of the model

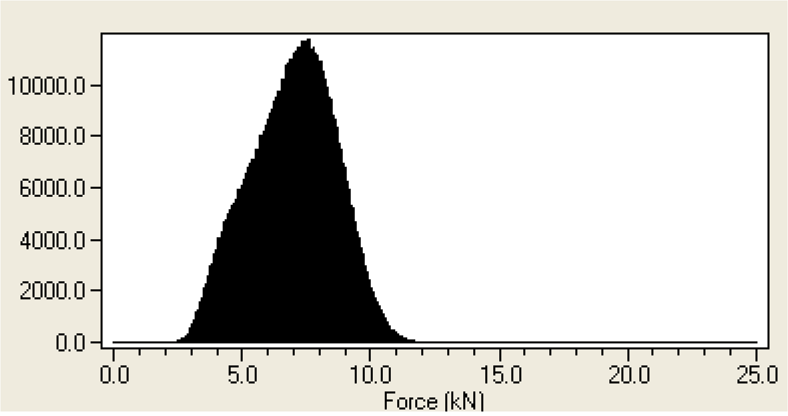
The outputs from the model obtained with the above inputs are shown below.

Bolt-1



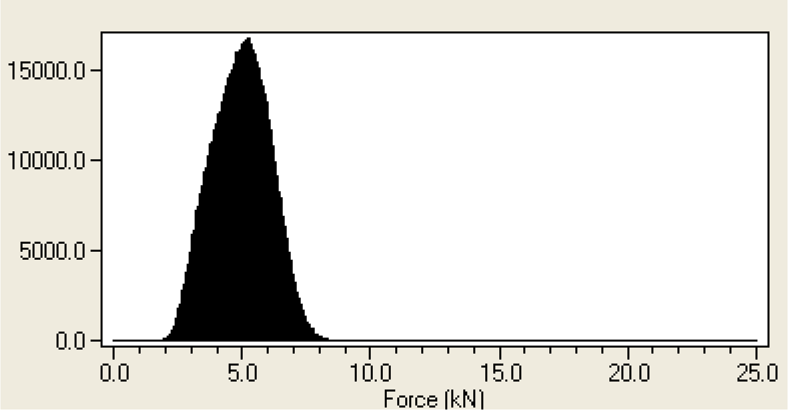
0 in 1 million > 16kN
2 in 1 million > 15kN
194 in 1 million > 14kN
3281 in 1 million > 13kN
23387 in 1 million > 12kN
90492 in 1 million > 11kN
227930 in 1 million > 10kN

Bolt-2



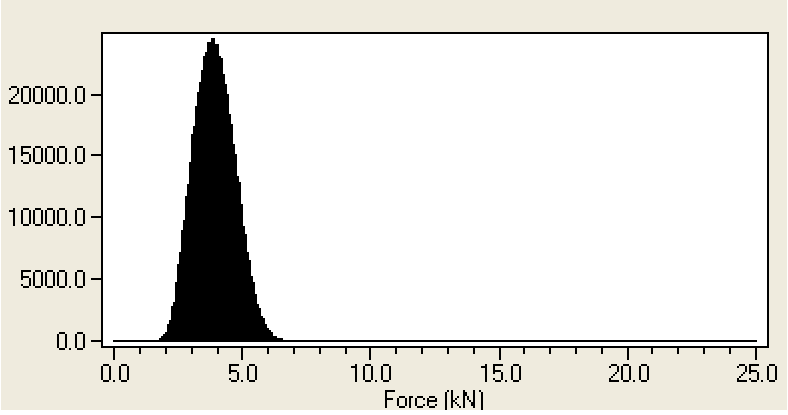
0 in 1 million > 13kN
49 in 1 million > 12kN
1803 in 1 million > 11kN
21109 in 1 million > 10kN

Bolt-6



0 in 1 million > 10kN

Anchors For C2, and nearly all C3 activity, the load on the anchors is no more than twice the climber's body weight. However, the possibility of a higher demand from a top-roping fall is nevertheless a possibility and needs to be analysed. This is presented in the figure below.



0 in 1 million > 10kN

e. *Conclusions*

- The first bolt takes the highest loads, and in specifying the first bolt, we can apply that specification to all bolts.

- The distribution is long-tailed on the high side meaning the strength of the bolt will need to be very much greater than the average requirement if it is to meet a high PFD requirement.

15. DESIGNING BOLTS TO HANDLE THE DEMAND

a. *Matching strength with the required PFD*

We see from the conclusions in sect. 13g that the safety integrity requirements come down to a target PFD of $< 4 \times 10^{-6}$ for individual bolts, and $< 5 \times 10^{-7}$ for anchor assemblies.

Dealing first with bolts, we see from sect 14e that the demand placed on the first bolt far exceeds that on the other bolts because it handles the highest fall factors. We also see from the model output at sect 14d, the prediction that less than 2 in 10^6 demands will exceed 15kN. Thus we have grounds to conclude that a 15kN bolt will provide the target PFD.

Dealing with the anchor assembly next, we find from sect 14d that anchors are normally loaded at no more than twice body weight, say 2kN worst case. Even considering the rare event of a top rope fall, the demands are relatively modest as is shown in the same section. However, due to the nature of the exposure to harm analysed in sect 13, anchors demand at least an order of magnitude higher security than bolts, and given that extrapolation to probabilities beyond 10^{-6} is likely to be increasingly error prone, common sense dictates the use of a redundant assembly comprising two independent bolts. This is current best practice for climbing anchors, and has the effect of reducing the required PFD per bolt to a more manageable value of $< 10^{-3}$. From a practical point of view this means we can specify identical bolts throughout the climb provided two of such are used for every anchor to provide redundancy.

b. *Relevance of EN959/UIAA123*

The European Standard EN 959 -2007, "Mountaineering Equipment - Rock Anchors - Safety Requirements and Test Methods" is the basis of a similar standard published by The International Climbing and Mountaineering Federation as standard UIAA123, "Rock Anchors".

Both standards describe minimum strength requirements for the hardware - part known as the "bolt", or sometimes the "bolt and hanger" depending upon the actual design. It should be understood that when these publications refer to a "rock anchor" they are talking about what we refer to as a "bolt". When we talk about an "anchor", this is a multi-bolt assembly not referenced by these standards.

The test regime described in the aforementioned publications is intended to establish a minimum strength requirement when the bolt is installed in a 50MPa concrete test block. Thus, there is an assumption that field installed bolts will exhibit equivalent performance.

The strength requirements are summarised in the following table.

	axial load (kN)	radial load (kN)
EN959	15	25
UIAA123	20	25

Table 15.1: Standard Bolt Strength Requirements

Given that it is likely any bolt installed within the domain will be radially loaded on demand, it follows that a bolt compliant with either of these standards would meet the strength requirements we have derived in the preceding sections. Even for an EN959 compliant bolt, installed upwards such that it faces an axial demand, would suffice given our analysis points to a 15kN requirement.

We have not been able to find any reference as to how the technical committee for EN959 came to the 15kN figure, but it is interesting that our model indicates it would be the minimum requirement for any first bolt on a typical sport climb, should one wish to achieve a PFD target of approx. 1 in 10^6. And, as we have demonstrated in section 13, such a target is realistic for the first bolt on a maximally utilized sport climb.

EN959 compliant bolting hardware is readily available from a number of European manufacturers. This analysis indicates that by ensuring such hardware is used, the installers of climbing infrastructure would discharge a significant portion of their duty of care.

c. Selecting a style of bolt

Broadly speaking, there are two styles of bolts which could be used, both being EN959 compliant, namely, expansion bolts and glue-in bolts. Experience at Kangaroo Point Cliffs has shown that expansion bolts are more subject to maintenance issues than the glue-in variety. In particular, the fact that they can be undone with a spanner, post-installation, leads to problems with the hanger being removed, anchor sets being stolen, and so forth. Furthermore, the appearance of glue-in ring bolts is less visually intrusive within the park setting. Thus, current best practice would indicate that an EN959 rated glue-in ring bolt is the superior choice.

d. Selecting a bolt material

As noted in the domain definition, sect. 9b, the environment is mildly maritime, and the use of corrosion-resistant components is obligatory if maintenance is not to be a major issue. We have a decade or more experience of components at the Kangaroo Point Cliffs which indicates that 304 SS is adequate. It is sufficiently corrosion resistant that we don't need to specify a higher grade of steel such as 316.

e. Selecting the critical dimensions and glue type

For a hard rock type such as that at Kangaroo Point, a standard 10mm x 80mm ring bolt such as Fixe #014-A, when fixed with a suitable adhesive such as Powers Pure150 Pro, will meet or exceed the requirements of EN959. Such a selection aligns with current 'best practice' within the climbing community.

f. Verification of the strength of the selected bolt

Using Mike Law's[7] formula for the strength of a climbing bolt we have -

$$F = B\pi D(L - L_{cone}) + 0.32\pi L_{cone}^2\sqrt{C}$$

where -

$$L_{cone} = \frac{BD}{0.64\sqrt{C}}$$

and -

$F\ is\ failure\ load\ (N)$

$B\ is\ bond\ strength\ (MPa)$

$D\ is\ hole\ diameter\ (mm)$

$L\ is\ embedment\ depth\ (mm)$

$C\ is\ rock\ compressive\ strength\ (MPa)$

This formula is based on the contention that the ultimate tensile failure load will be the sum of the force required to pull a cone of material out of the surface, plus the shear force required to break the adhesive rock bond for the remaining length of the bolt. It has been shown to better represent reality, especially when predicting the strength of longer bolts in soft rock.

Substituting the following values -

$B = 10\ MPa$
$D = 12mm$
$L = 80mm$
$C = 60MPa$

we obtain a value of 25kN for the failure load.

The main assumptions applied are -

- The bond strength of the adhesive. The value of 10MPa is an estimate derived from Powers data for their Pure 150 Pro epoxy. It was derived by calculation from a range of twelve different limit state design figures for steel reinforcing bonded into 40MPa concrete. The actual figure obtained by regression of limit strength on bond surface area was 10.7+/-0.4MPa.The limit state figures have a conservative factor of 0.6 applied, thus we can assume that this bond strength will likewise be conservative.

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[7] Law M (2009). Soft Rock Bolting Guide. Retrieved Jun 14th 2013 from http://www.safeclimbing.org/education/SoftRockBolting.pdf

- The compressive strength of the rock is estimated as being between 50 and 100MPa, based on conventional hammer-test criteria. We have chosen a conservative figure in this instance.

The above calculations assume an axially applied load, while the majority of demands on a bolt are likely to be radially applied. However, for glue-in bolts, where the cross-sectional area is low, it is normally the case that all failures are failures under tension, since a radial load will crush the rock directly under the bolt until the load is predominantly tensile. Thus it is usual to find no major difference between the failure loads whether axially or radially applied.

Actual pull tests with 10mm ring bolts placed in good rock typically yield ultimate strength figures in the range 30kN to 40kN, as would be expected from the conservative factor of 0.6 applied to the adhesive bond strength.

16. SPECIFYING MAINTENANCE REQUIREMENTS

Based on overseas and Australian experience, the life expectancy for quality infrastructural components is greater than 20 years, and looking at current UIAA work, we'd expect this design to be conformable with their 50 year classification. There are four mechanisms by which the integrity of cliff infrastructure might be compromised, namely, disassembly, corrosion, abrasive wear and fatigue. The first two we can strike out because of our choice of design, i.e. all-welded design in corrosion-resistant stainless steel. The second two will be discussed below.

a. Requirements for bolts

i. Loss of integrity through mechanical wear

The Fixe ring bolt, when correctly installed, exposes only part of the ring beyond the surface of the rock. This ring is manufactured from 10mm dia. 304SS. If it is to wear at all, it can do so only via the agency of the aluminium carabiner of the quick-draw clipped to it. Normally, the quick-drawer is not loaded, so at most we have little more than the weight of the quick-drawer bearing on the lower inside surface of the eye of the bolt. Not surprisingly, wear of the bolt by this means is unknown.

ii. Loss of integrity through fatigue

As part of their normal function, bolts are subjected to the occasional transient load resulting from the arrest of a falling climber. As has been demonstrated in sect. 14, the magnitude of these loads will vary considerably, and it is likely that some loads will be significant compared with the ultimate strength of the bolt. Given that in Table 13.4 we estimate that under worst case conditions, first bolts taken as a whole could experience > 24,000 load cycles per annum, then it is clear that on average any one of the thirty first bolts could experience something in the order of one thousand load cycles per annum. Thus it is reasonable to ask whether significant loss of bolt integrity through fatigue could be an issue. Note that here we are not being specific about the mode of the fatigue weakening. It could be metal fatigue propagating a crack through a point of stress concentration within the eye or upper stem of the bolt itself, or it could be the effect of structural collapse of the rock within the immediate vicinity of the bolt, or it could be a progressive delaminating of the adhesive from the bolt stem or yet another mechanism.

We have found a few anecdotal reports where bolt failure has been attributed to metal fatigue, but little in the way of well designed studies. However, Mike Law quotes data from Pircher[8] that clearly shows fatigue could be a factor. This author demonstrated that repeatedly cycling a 10mm glue-in ring bolt to 25kN measurably reduced the failure strength after 100 such cycles. When the bolt was set in 50Mpa concrete, the bolt failed at 92% of that expected. However, when set in 26MPa concrete, the failure occurred at the lower value of 73%.

Law also presents[9] some fatigue tests he carried out for bolts of various types inserted in soft sandstone (probably < 20MPa). Here the dominant failure mechanism was the progressive destruction of the rock supporting the bolt. A 10mm ring bolt withstood progressively increasing repetitive load cycles finally failing at cycle 44 after a set of 5 cycles at 25kN. In total, it withstood 28 cycles greater than 12kN.

Apart from being alerted to the possibility of loss of integrity through fatigue, it is difficult to extrapolate from the above figures except to note that repeated cycling to a force as high as 25kN is something that is physically impossible within our domain, and that the rock at Kangaroo Point is harder, rather than softer, than the 50MPa test piece used by Pircher or the 20MPa rock used by Law. Any extrapolation we do, needs to be highly conservative, and thus we have settled on a fatigue life figure of 100 cycles in excess of 12kN, remembering that 25kN is the nominal design strength of the bolt we set in sect.15.

How long a period is *100 cycles in excess of 12kN*? From Table 13.4 and sect 14d we have everything we need to answer that. Firstly, from the demand rate on all twenty first bolts in the domain we can get the demand rate for a single bolt, and then from the distribution of the magnitude of demands on the first bolt we can get the proportion of all demands exceeding 12kN. Thus the product of these two quantities gives us demand rate on the first

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[8] Pircher M (2006). Testing of Rock Climbing Anchors. J. Testing and Evaluation, **34**, N5 Paper IDJTE14117

[9] http://routes.sydneyrockies.org.au/confluence/display/thelab/Fatigue+testing

bolt for those demands in excess of 12kN. From there we easily calculate the number of years it takes to clock up the 100 cycles.

This calculation is illustrated in the table below for the first and second bolts. For the higher bolts the time it would take to achieve *100 cycles in excess of 12kN* is immeasurably long. It can be seen that according to this analysis, only the first bolt is at all likely to accumulate sufficient load cycles to warrant suspicion of loss of integrity through fatigue, and only then under the most stressing input assumptions about rate of usage.

Table 16.1: Duration required for a bolt to accumulate 100 cycles in excess of 12kN

	type	**demand rate (demands p.a)**	**proportion of demands > 12kN**	**demand rate (demands > 12kN p.a.)**	**duration to accumulate 100 demands > 12kN (years)**
bolt-1	primary	21	0.023	0.475	211
	stressed	826	0.023	18.988	5
bolt-2	primary	21	4.90E-05	0.001	98883
	stressed	826	4.90E-05	0.040	2472

iii. Recommended maintenance

An inspection interval of once every five years should be adequate. Any bolt showing signs of damage or deformation either of the bolt itself or the immediately surrounding rock should be replaced. In the unlikely event of the utilization of the domain approaching the worst case assumptions in sect. 13, it would be a wise precaution to replace all first bolts every 5 years.

b. Requirements for anchors

i. Loss of integrity through mechanical wear

There are two wear mechanisms for chain anchors that are significant. Firstly, the components of the anchor wear by rubbing one over the other, e.g. chain link to chain link, chain link to bolt eye, chain link to ring. Secondly, the rope, always abrasive loaded to some extent, running through the carabiner.

The first is a slow process, and the hazard it presents is constrained by the redundancy of the anchor. The second is a surprisingly rapid process which means the replacement of anchor carabiners is a major maintenance requirement for a sport climbing area.

Carabiners specifically manufactured for the use on anchor chain sets, such as the Fixe Draco, are designed to tolerate substantial amounts of wear before they become unfit for purpose.

ii. Loss of integrity through fatigue

Although anchors are subjected to the largest number of load cycles per annum, the load is typically less than 0.2kN. By reference to Table 13.4 we can see that the worst case used of stressed input assumptions gives us the possibility of 601,000 load cycles per annum distributed across all thirty climbs within the domain. Thus we should allow for 20,000 load cycles per anchor, per annum.

Given the loading is approximately 0.5% of the ultimate tensile strength, and given the bolt profile and the manner in which the eye is recessed into the rock it seems reasonable to assume that such cyclical stresses as it is likely to experience are well below the fatigue limit of the material of the bolt.

Further to this, the anchor is comprised of two such bolts, thus providing redundancy in the event of a single bolt failure.

iii. Recommended maintenance

An inspection period of 1 year is required. The carabiner should be replaced if its thickness is reduced to 70% of original. The chains and their attachment points should be inspected for fretting wear, and the entire anchor replaced if any component has its critical material thickness reduced to 80% of the original. The bolts should be inspected and any bolt showing signs of damage or deformation either of the bolt itself or the immediately surrounding rock should be replaced.