SOFT ROCK BOLTING GUIDE

Introduction

This guide is focussed on placing anchors in typical soft Blue Mountains sandstone. The rock strength is well below most other climbing areas, and requires different techniques. A series of test were performed as part of Steve Hawkshaw's thesis, and this document borrows heavily from that testing and analysis.

The short version for people who don't have time to read it all

Use glue that works (ask around). Learn how to use it, and know what the correct mixture looks like. Take samples as you go.
Drill in sound rock
Place them in good spots, if in doubt, toprope the route first
Clean holes well
With rings, recess the eye by the thickness of the rod
Buy appropriate quality anchors, Ubolts or rings.
If you make your own anchors then:-

- Make them long (Rings > 120 mm, Ubolts > 90mm)
- Either clean-grind-notch, or thread, the anchor.
- Only weld if you know what you are doing

Practice first.
Test them before releasing them on the public (either fall on them or test them; Appendix 8)

Summary

In practice, bolts don't fail at 20 kN plus loads, taking large amounts of rock with them. Of the glued anchor failures that have occurred about 60% are where the glue didn't set (incorrectly mixed, out of date etc) and 40% are rings loosening due to an insufficiently notched eye.

What is a good bolt?

The ideal, unattainable, bolt is bombproof, foolproof, permanent, unobtrusive, and cheap. What best approaches this depends on the local rock and available technology.

What's available?

Carrots: tapered 10 mm or 3/8" bolts pounded into slightly smaller holes.
Expansion bolts: A bewildering array is available. These are good in hard rock, but require a fixed bracket. Corrosion is a problem unless they are stainless and they generally require a 12 mm hole to get good security. They are convenient on roof climbs.
Glue in bolts: 10mm s/s bolts glued in. A fixed bracket is sometimes in place also.
Glue in rings: 8 mm or 10 mm s/s welded rings glued in.
Glued in U-bolts: 8 mm or 10 mm s/s rods bent into a 'U' shape and glued into 2 holes.

What are commonly placed now?

In Blue mountains sandstone most older routes are protected on mild steel carrots which are up to 30 years old and generally look ok. On chopping sprees you generally find one in 20 of these is a bit dodgy, but it's hard to assess from the outside. On more recent climbs there are either glue in S/S bolts with or without fixed hangers, or glue-in rings or U-bolts.

On harder rock such as Nowra and Victoria, there are expansion bolts, some glue-in rings, and a few carrots, often S/S.

Strength Requirement

In Europe anchors conform to EN-959 (figure 1). This calls for a direct (axial) pull-out resistance of 15kN and in the direction of fall (radial) 25kN in concrete with a compressive strength of 50N/mm².

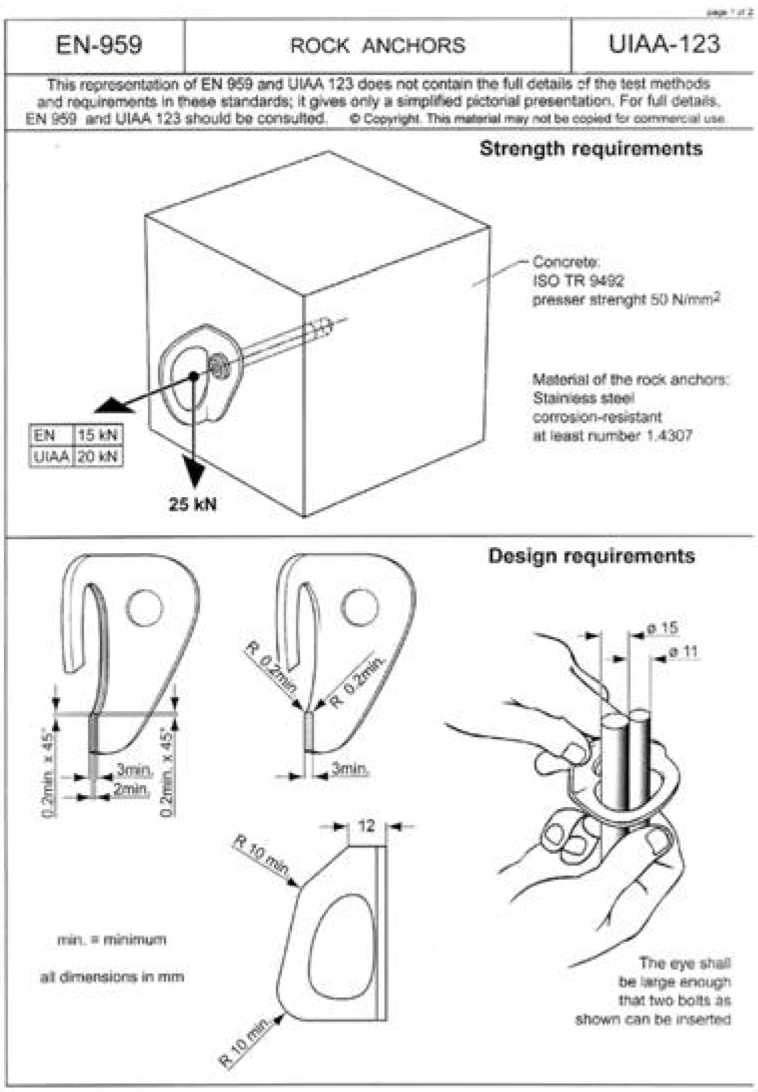


Figure 1 EN 959 strength requirements

A rope has a maximum impact force of about 8kN, these can be almost be doubled at a runner to 16kN. Most sport climbing falls are down at about 3kN. Grigri's etc will raise impact forces (Sticht plates and ATC's etc slip at 3kN, while a Grigri on a thick rope may only slip at 9kN). Modern low impact ropes will reduce these forces considerably. The rated strength requirements are comfortably above what can be achieved in the field.

Failure modes

By seeing the ways that bolts fail, one may have a better idea of what to avoid. Bolts will fail by the weakest link in the chain of anchor strength, rock strength, or rock - anchor bond strength.

In practice, bolts don't fail at 20 kN plus loads, taking large amounts of rock with them. Of the glued anchor failures that have occurred about 60% are where the glue didn't set (incorrectly mixed, out of date etc) and 40% are rings loosening due to an insufficiently notched eye.

Anchor Strength

This is the simplest factor to calculate, stainless steel (304) has a nominal tensile strength of $700N/mm^2$, and mild steel has a tensile strength of about $250\ N/mm^2$. The strength of the bolt will then be its cross sectional area in mm^2 multiplied by this, for example a 10mm diameter stainless bolt has a strength of π x 5^2*700 = 54977N = 55 kN = 5.6 Tonnes.

Breakage is pretty unlikely with most modern options but worth worrying about on:-

A) Rusted mild steel bolts will be weak. On seacliffs mild steel looks pretty tragic.

B) Yosemite style split pin 1/4" compression bolts from the 70's (found occasionally on granite, but there's one on Starkosis!), rusted Petzl caving bolts (not designed for climbing, but used extensively at Tarana) and possibly very rusted dyna-bolts or Rawl bolts.

C) Fatigue loading may be a problem on threaded shafts, corrosion will exacerbate this problem

D) Welds can be a problem for fracture or corrosion

Rock strength

In hard rock, no matter which way modern bolts are loaded the failure is in tension regardless of the load direction. The rock crushes under the bolt and it tries to slide out even when radially loaded, as can be seen in the following picture.


Figure 2 Rock crushing in shear test

In soft rock, there is more rock crushing under the anchor and this complicates the issue

Under the loadings found in climbing rock failure often happens with soft rock or overdriven bash-in bolts on hard rock. In soft rock the culprit is an anchor which is too flexible (i.e. 8 mm stainless welded rings or bobby pins, long mild steel bash-ins). The bolts flexes and places the bulk of the load on the edge of the hole, this locally collapses and then the leverage is worse and you're left with a crater. Use of 10 mm rings will normally eliminate the problems, but on true pox which is going to see a lot of falls use a big 10 mm or thicker "U" bolt (there are 14mm Ubolts at Berowra!). Karabiner movement or rope wear can “excavate” around an anchor in soft rock also.

The force of the over-pounded carrots is more than enough to shatter the rock, the cure is to use a bigger hole or more filing on the bolt. Note that too much taper makes the bolt unreliable (it’s only holding on the first few mm of the interference fit).

Rock is not uniform, it can have cracks, inclusions, pockets and built in stresses which can effect its strength so you really want a good margin of error here. Break out can be calculated using the projected area of the cone of failure.
The American Concrete Institute (ACI) gives the following formula for calculating the concrete load bearing capacity:-
$R = 0{,}32\pi L^2 \sqrt{C}$ Eq 1
Where
R = Rock failure load (N)
C= material compressive strength (N/mm^2 or MPa – same thing)
L = anchor embedment depth (mm)

Using a rock compressive strength of 30 N/mm^2 and an effective embedment of 100 mm we get 55kN, which is massive! See appendix 3 to see why this simple model overestimates the strength of anchors in tension.

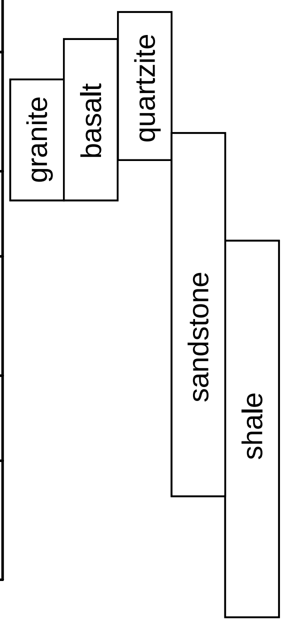
Rock is often variable in strength and shot through with holes and cracks, which brings down the strength. For instance NSW sandstones might test from 10 MPa (Dogface) or less, through 30 MPa for most Blueys cliffs to 60 MPa for Nowra. I believe that the steep “bomber” orange rock in the Blueys is probably weaker and wetter inside than much of the vertical black rock, though no real testing has been done on this.

The Equation 1 formula for strength has length squared. We can see this by reducing the embedment in the above example by one half to 50mm which gives a strength of 13.7kN or one quarter of the previous result. Use longer bolts and try to find sound, homogenous rock for placements.

The EN standard test block has a compressive strength of 50N/mm^2 , this is low compared to most rock types, but high compared to Blue mountains sandstone. Here is a table of the range of strengths for typical rock types. To get a rough guide to compressive strength you can use this standard geologists test.

Table 1 Field test for compressive strength

Description	Compressive strength (MPa)	Test method
Very strong	100-250	Requires many blows of a geological hammer to break intact rock specimens
Strong rock	50-100	Hand held specimens broken by a single blow of a hammer
Moderately strong	25-50	Firm blow with geological pick indents rock to 5mm, knife just scrapes surface
weak	5-25	Knife may cut material but too hard to shape
soap	1- 5	Material crumbles under firm blow of geological pick, can be scraped with knife



When you drill hard rock, the rock strength you’d guess from the surface appearance and drilling is consistent as you go in (as it’s often igneous or metamorphic rock). However, in a lot of soft sandstone there’s a skin of re-deposited bonding material (it travels dissolved in the water to the surface, then the water evaporates) over much weaker material with less bonding material in it. The rock is hard for the first 5-10 mm, then much softer. This may be disguised if the rock is internally wet, as quite a lot of the drilling power is taken up in moving the muddy paste out of the hole

Rock-anchor bond

This is achieved by mechanical force for an expansion bolt, and glue bond and shear strength for glue-ins.

Bolt/Rock Interface.

Either the mechanical action of the bolt or the adhesive power of the glue used has to transmit the load from the bolt to the rock.

Mechanical anchors achieve this by creating expansion against the hole. Mechanical anchors in soft rock may crush the rock where they expand, allowing pullout or loosening.

Glue in anchors need bonding from the glue to the shaft, and also from the glue to the rock. IN many ways this is less adhesion and more mechanical keying into roughness in the rock surface, thin runny glue probably improves this.

All glue in anchors have the potential problem of the glue either failing to set, or failing to bond to the stainless shaft. Glue failure is caused by incorrect mixing, wrong mixture, a dodgy cartridge (not delivering the right mix), not pumping through enough glue to mix fully in the mixing nozzle. Some glues are too thick to use, and are thinned with a solvent, which may evaporate. A common problem is loss of the styrene solvent so the flow of one of the components is retarded or stopped, leading to a mix that is weak or doesn't set at all (this can often have a hard crust on it so that it looks set). Often there is insufficient glue in a capsule for a reasonable length bolt and the 20 mm of bolt near the surface has no adhesive, a little unsettling.

Glue may fail to bond to the shaft. Stainless rods have a greasy coating on them to discourage staining and corrosion before they're sold, you can't expect this to bond at all. Washing the shaft with some solvent, then detergent and rinsing will remove this, after this sanding or grinding will help. Note that when you grind stainless steel with a wheel that has ground other ferritic material, you may introduce stuff off the wheel which may start corrosion, so don't do it within 15 mm of the rock surface. Threading, notching, or welding blobs on are essential. Assume that it doesn't bond at all and rely only where the glue keys into the shaft by means of some notches or threads.

A ring may loosen in the rock, this is common with ring bolts where the eye has not been sunk sufficiently far into the rock. Any side forces on the eye (falling off to the side) may break the glue bond very easily (there is major leverage available there). Sink it at least the thickness of the bar it's made from, the bar should be buried and it should look like a Ubolt.

You can calculate the theoretical strength which, assuming you have provided sufficient keying to the bolt and the hole, depends on the adhesives strength, hole diameter and depth.

One formula (Uniform Bond Stress Model) for this is:

$$G = B\pi DL \qquad \text{Eq 2}$$

Where
G = Glue failure load (N)
B = Bond strength (N/mm^2)
D = Anchor diameter (mm)
L = anchor embedment depth (mm)

Manufacturers seem reluctant to publish figures for the bond strength but most researchers for the construction industry give values of 8-10N/mm^2 for polyester and about 15N/mm^2 for epoxy. For the product you wish to use you can normally reverse calculate the value from the ultimate pull-out strength tables that most suppliers publish.)

Assume that the shaft doesn't adhere except by threading or notching AND clean and surface grind.

For those of the " a few angle grinder cuts in the legs will do" school of thought here is a photograph of one of two bolts recovered after being ripped on a sport route in Hollental, Germany. The climber fell on the bolt after a hold broke, ripped it and the next and decked suffering severe injuries. The accident was reconstructed and the load calculated at 5 to 7kN. The glue was analysed and found to be fully cured and satisfactory but you can see for yourself how well it stuck to the bolt!

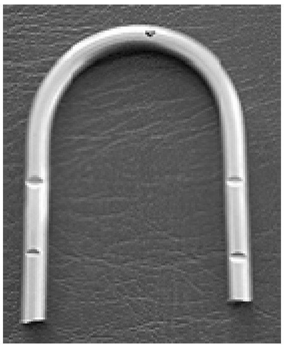


Figure 3 Ugly death U (Taken from "Hakenausbrüche beim Klettern." D Stopper. Leader Safety Research, Deutsche Alpine Verein.

Despite all this, when glue-ins fail, there's no massive cone of rock attached to them, the failures are generally where glue hasn't mixed properly, or with insufficiently recessed rings that have twisted loose.

What to place?
This depends a lot on the rock type, what you want (permanence, cost, convenience). Carrots are quick, but require the highest levels of skill and judgement. Expansion bolts are quick, but also require a fixed hanger which are obtrusive, are hard to retreat off, and are also among the most expensive. Rings and U bolts are convenient as retreat is simplified, and if well placed, can be unobtrusive. Generally, glue in type anchors are not suitable for drilling on the lead. The table at the end of this document lists the advantages and disadvantages of most common fixtures.

	Price	Life	Visibility	Strength	Suitability for soft rock	Suitability for hard rock	Weaknesses
Mild steel carrot	$0.50	Poor to fair	Low	Variable	Fair	Poor	Outward force, corrosion
S/S Glue-in bolt No Hanger	$2.50	Good	Low	Good	Good	Good	Glue failure, greased shaft
S/S Glue-in bolt With hanger	$6.00	Good	High	Good	Good	Good	Glue failure, greased shaft
Expansion bolt-plated	$3.00	Poor to fair	High	Variable	Poor	Good	Loosening, corrosion
Expansion bolt-Stainless steel	$6.00	Fair to good	High	Variable	Poor	Good	Loosening
Ring bolt	$7 - $1.50	Good	Medium	Good	Fair to good	Good	Glue failure, greased shaft, sensitive to twisting
“U” bolt	$6 - $1	Good	Medium	Very Good	Good	Good	Glue failure, greased shaft
Injection glue per hole	$1.00 to $1.80						

How to bolt?
There are two things to discuss here, where to place bolts and how to bolt an entire route.

Where to place bolts
This is about where to place your bolts once you have your general scheme of things organised. It is important that the first ascentionist carefully considers where each piece is placed, taking into account all safety considerations. Bolt placement should not disadvantage climbers with shorter reach. When climbing above ledges, often you need to place bolts closely to avoid hitting the ledge. Don’t bolt new routes close to existing bold routes, it obliterates them

Tap around with a hammer and check the rock is sound, you can’t tell when you’re drilling. Place them at least 150 mm away from cracks or arêtes

If your route goes up a “staircase”, try not to place the bolts on the wall at the back of roofs as it causes lots of drag, and falling bodies tend to slam into the wall (figure 5)

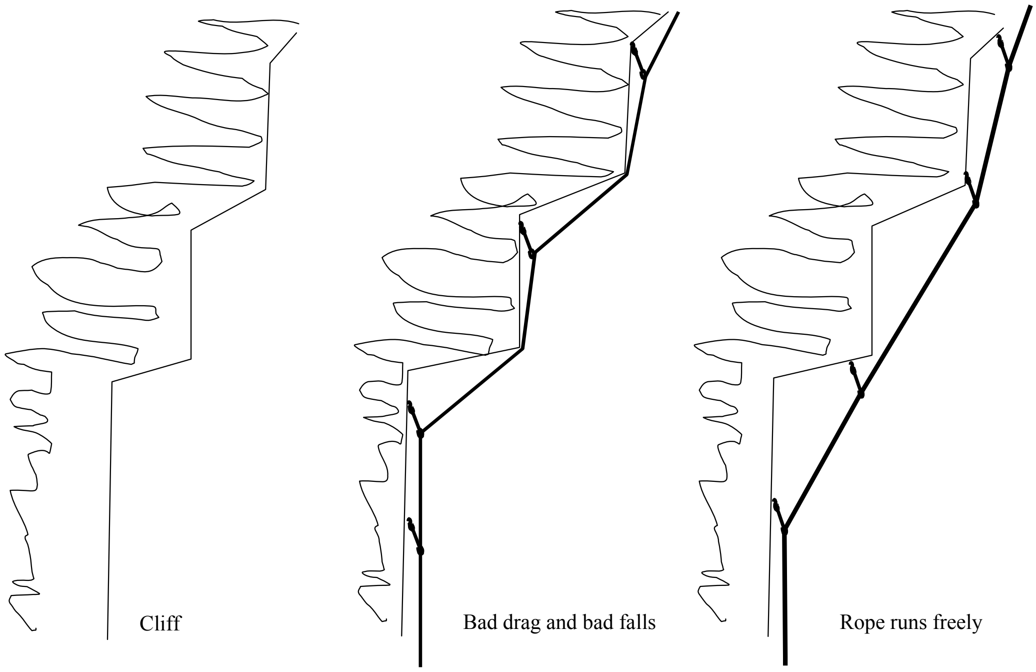


Figure 4 Think about rope run and potential falls

How to Bolt

Hand drilling

Either use a handmade rig for soft rock (bar or 25 mm round steel with a wood bit ground slowly to a chisel point) or one of the commercially available sets. Drilling off a poor stance is not only tiring, it is also hard to place a decent bolt, and if you’re on a really poor stance you’re tempted to think that a 30 mm hole is enough.. See appendix 5 for more details.

Power drilling

The major advantage is the ability to place the best possible bolts. Disadvantages are weight, cost and noise (for petrol drills). Keep the SDS grooves clean and lightly greased, your machine will last longer and drill faster. Ear plugs are worthwhile, and safety glasses are good when drilling hard rock

Drilling from the ground up

A good look at the route should give you an idea of where to go and what type of positions you'll be drilling from, what type of stances or gear you'll be drilling from. On many climbs you can't put up the best possible climb from the ground up as you are forced to follow stances or hook placements rather than the best climbing.

Drilling from abseil

Unless it's easy, the first few times you bolt a new route, top rope it first to see where you need pro, and where you can clip from reasonably. If it's steep you might need to place natural gear, dynabolts (which are hard to remove), or coach screws (which are easily removed) to keep you in contact with the rock. Everyone gets it wrong occasionally, and some people get it wrong all the time.

Abseiling and Ascending

This is hard work as you are carrying as lot. Scary too! Either use standard ascenders (the caving SRT rope-walking system doesn't seem to work so well on overhung bolting thrashes, just one to your waist, and one to a foot sling, also attached to your waist). Other people use an ascender with one foot loop above a GriGri on the harness, but this is more tiring.

Where to place bolts

As a general rule, keep it interesting, but keep it safe, extra bolts on the crux are nice for dogging moves, and suckers will pause and clip them, adding to the grade and the route's rep. But at the same time, if the climbing gets easier, spread the bolts a bit to maintain the strain. The first 10 m is probably the most dangerous, and where the bolts should be close together.

Where to put the first bolt?

If the first bolt is 3m up, and the second is 5m up, most people will hit the deck if they fall clipping the second bolt. Solution? Put the first bolt a bit higher and people will either climb up to it a bit more cautiously (people rarely fall off death routes) or stick clip it.

Anchors and lower-offs

An anchor is something you, umm, anchor yourself to. And a lower-off is an anchor that you can lower off. Rocket science hey!

What are the requirements of each? For anchors, the old rule of thumb was to be able to be stronger than a rope or 'biner, by which time you'd be strained through your harness and bubbling pinkly on the ground. Better two or three anchors which hold 2 Tonne each, than a single 20 Tonne anchor which might fail occasionally.

Under a roof is a good stance in rain, but under a big fall, the second can slam up into the roof. A good configuration for (semi)hanging belays is one bolt in the line of the climb, one bolt out to the side for the belayer, and a third bolt a metre higher, both as part of the belay, and to act as a first runner. Be aware of the likely directions of forces, though a good bolt is multi-directional.

Lower-offs see much lower forces and the major criteria are the ability to dissuade idiots from suicide, and resist wear. Try and avoid placing them in positions where the rope will wear badly. On climbs which see any traffic, lowering off directly through the eye of rings will wear them out in a matter of years. In these cases, a replaceable link such as ‘biners or shackles is a necessary, though slightly messier, option

Figure 5 Badly placed Ubolt showing major wear after 4.5 years service

The standard setup with a top ring and an offset ring (presumably as a backup) is not great. Both rings still wear and will have to be replaced eventually. You can’t place standard shackles on these to reduce wear as the ropes will twist a lot. Twisted shackles are available but are more expensive.

Chains get around some of the problems but will be prone to rust after a few years, and are highly visible.

My favourite solution is to have a top piece which can be a ring or a U or a bracket, with a shackle or ‘biner on it. Directly below this is a large “U” placed horizontally, you thread the rope through the lower large U and the shackle on the top piece.

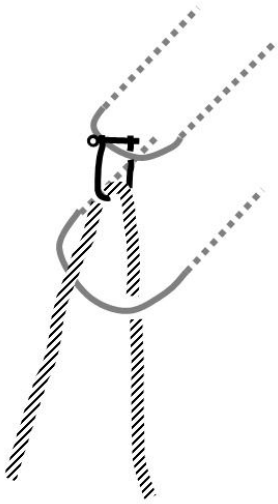


Figure 6 Lower-off with 2 horizontally placed Ubolts.

Angle of placement

In the old days carrots were angled downwards at about 10 – 15 degrees, this doesn’t really add much to the holding power, but keeps the bracket or biner closer to the wall. As the rock becomes steeper the amount of rock underneath the anchor is reduced disappears, so you are best placing them at close to right angles to the rock.

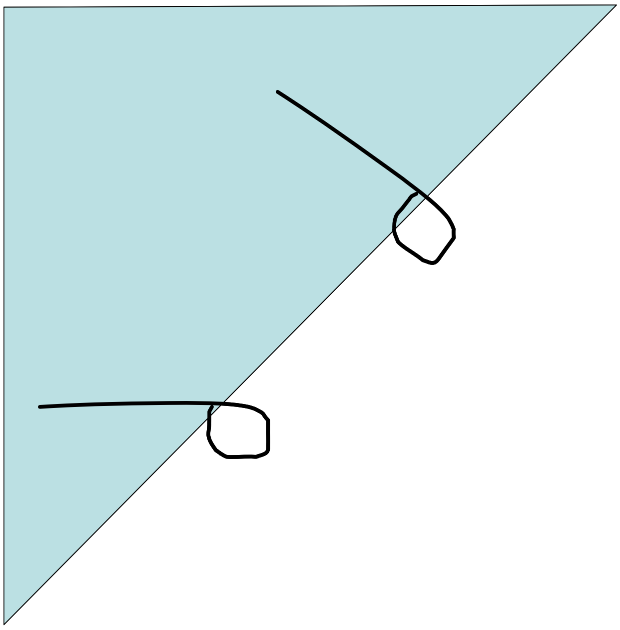


Figure 7 Steep angle of drive can leave insufficient rock under the anchor. The upper one is better.

Rebolting

Many older routes were put up with hand-drilled protection which is even more unreliable than modern gear. This factor, and the age and possible corrosion of many of these older pieces, suggests that replacement may be a good idea. It’s probably best to do this in consultation with other local climbers on position and manner of bolting.

Don’t start a bolting/chopping jihad, so respect the local ethics. Rebolt, don’t retrobolt. If a route is mostly fixed gear, and the local ethics permit it, fully bolt it and add lower offs etc. If it is a trad route with one bolt, leave it that way (but you can replace the bolt). In other words, try and maintain the essential character of the climb, be if safe or bold. Don’t retrobolt something just because you’re too sacred to do it, you might become a better climber and regret it. Try to lead (or at least top rope) the route first so you know if they need moving in terms of clip-ability, safety etc.

Bolts were often placed badly on the FA (through ignorance or poor gear, you can’t place an aid bolt with a hand drill if you’re already using one hand to hang on), when rebolting use the one meter rule, move them about up to a meter without even worrying what people will think (unless you fuck it up). It’s a good idea to climb the route before rebolting to check out what it needs. Test the new bolts before releasing them on the public.

Corrosion:
Apart from general rusting of a mild steel bolt, which should be visible, there are a few other worries. Stainless steels can have a few maladies, particularly around welds if used in marine or industrial environments, its probably best to either use bolts made of an alloy which is resistant to this weld "sensitisation" (316L) or to use bolts which don't incorporate a weld (straight glue in bolts, bobby pins or U’s).

Figure 8 Mildly corroded mild steel bolt on seacliff

Stress corrosion Cracking (SCC)
This has mostly been a problem in Thailand (high ambient temps and Chloride ions in sea water), and predominantly in mechanical bolts (crevice corrosion). There was talk that some rings had failed (which would not be surprising as the residual stresses from forming are considerable, and home welding can lead to Cr segregation). All the stainless bolts and U’s I've slammed into the Sydney seacliffs are still behaving themselves.

There are standard curves for the stress that can lead to SCC in SS (somewhere, maybe in the ASM handbooks). The typical methods of reducing this are large forming radii, heat treatment (re-normalisation I think), and passivating (which is pickling in acid to speed corrosion and arrive at a uniform layer of corrosion product, probably not best for critical components without stringent quality control. As far as I can work out, the vast majority of stainless corrosion is in mechanical bolts.

Rings may have a problem with weld sensitization if the welding isn't done fast enough. Welds and U's have a potential problem with crevice corrosion if the glue allows water down beside the bolt. Stainless steel corrosion is pretty rare, but is worst in warm tropical seaside environments (where titanium rings have been used), there's no real indication that it's a problem here.

Shock loading

We have a preconception about shock loading that it is more extreme than normal loading, in some cases this is true but the strain rates have to be very high and occur in a very short time. Part of this preconception stems from our experience with hammers – it’s simply a way of concentrating a large amount onto a nail head. In climbing falls using ropes, the energy is dissipated over a longer time, and strain rate effects should be able to be discounted. Take the same fall on a steel cable, and because the very limited stretch, the forces will be much higher (10 times roughly), will occur over a shorter time, and will probably cut you in half too.

Appendix 1 Bolt Types.

This section is copied extensively from Bolt Products - (http://www.climbargolis.com/Glue-inBoltDesign.htm).
Other info is available from the BMC (http://www.thebmc.co.uk/bmcNews/media/u_content/File/equipment_advice/bolt_funds/Users_guideLR.pdf) , the American Safe climbing site (http://www.safeclimbing.org/), and the South African bolting site (http://www.saclimb.co.za/bolting.html) (which has some very confused testing).

Summary
Either buy a well made anchor, or know what you are doing if you make your own. They should be 8 or 10 mm diameter (prefer 10mm for soft rock). The length should be > 90 mm for Ubolts and > 120 mm for rings. The surface should be cleaned-ground-notched, or threaded. They should be manufactured from stainless steel for corrosion requirements, the usual material being 304 or 316 stainless. Don’t bother gluing in anything that isn’t stainless or better (Duplex stainless steels or titanium are very corrosion resistant, but expensive).

Forged Eye Bolt.
The one shown is a Petzl Collinox, the smaller of the two models they make and a fine product. 10mm diameter shank grooved for better adhesion.

Figure 1.1 Collinox forged eye-bolt

The lack of welding avoids cracking or corrosion problems, and there is no weak area on the shaft due to heating during the welding process.

The Bühler Bolt.
“Common in the Frankenjura. Made either from 6 or 8mm stainless steel rod. Usually 80mm long legs for limestone and up to 150mm for sandstone.. Claimed to be the best bolt for home construction, but probably too flexible for soft rock (two 8mm shafts have 22% more deflection under load than a single 10mm rod). Shown is a home made bolt with a particularly large eye made from 6mm stainless. Note the large and

rough weld, this is needed to provide resistance to extraction as the glues adhere very poorly to stainless steel." [Bolt Products]

Figure 1.2 Buhler bolt

Figure 1.3 10cm Buhler bolt with less welding and some notches

Commercial forged twin rod bolt

"This is a commercially made bolt (from AustAlpin) using 8mm rod forged down to give a 12mm shaft with teeth to provide adhesion. Cost €4.95 + glue. Note the curved shape of the upper part of the eye introduced to reduce the chance of involuntary unclipping. " [Bolt Products]

Figure 1.4 AustAlpin bolt

Bolt Products twisted bolt

These are twisted from 6mm or 8 mm rod, are very solid, and can be removed if necessary by twisting out. In some configurations one spiral can ride up over the other spiral and jam the bolt in its hole; however this probably depends on the direction of pull and can't be relied on. There is no weld to crack or corrode.

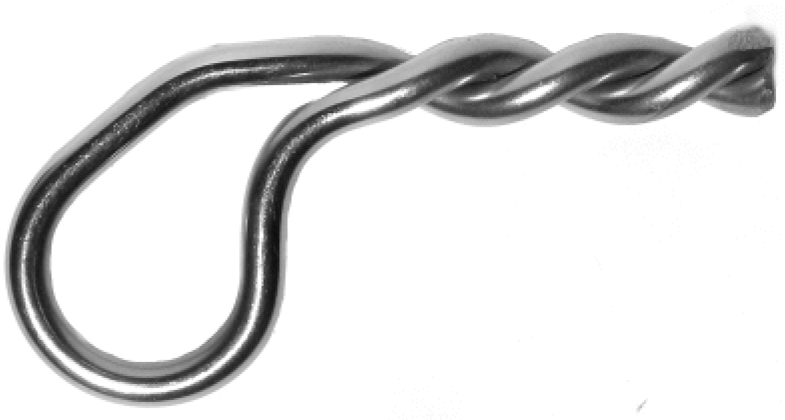


Figure 1.5 Bolting products 8mm twisted bolt

The Staple or U Bolt.

Lifted from Bolt Products:- "You may or may not be aware that these were in common use in Germany for many years. The Germans being thorough chaps go around testing bolts at regular intervals and the results led to a decision to remove all staples immediately as none achieved the required test figures. The test results for staples were not published by the DAV as far as I know but we made and tested some. 8mm dia rod with 80mm legs achieved around 6 to 8 kN, When I knurled the legs to improve the bond the rock failed, generally at around 12kN. Examination of the failure showed that drilling two holes so close together seriously weakens the rock, according to friends in the quarry industry the drilling produces micro-fractures and these link up producing an area of shattered rock between the holes. (A similar effect to when you try to fit a expansion plug in a masonary wall near to an old one). Another problem we noticed was that on the bolts with bonding failure only one leg failed, implying that the load is not evenly shared, therefore the bonding for <u>each</u> leg must be capable of withstanding the proof load.

This is one with threaded legs for better adhesion and extremely wide leg spacing I made up for testing some years ago. " [Bolt Products]. No test results are given for this slightly odd Ubolt. Wide leg spacing in thin Ubolts gives a crushing load between them, which is one reason to avoid this design.

Figure 1.6 Large ugly Ubolt

It is interesting to speculate on why they are so despised, despite Steve Hawkshaw's thesis giving good results for them. Possibly their ease of manufacture leads people to make them with no possibility of the glue bonding to them.

However, the test results for Ubolts are high. As shown in appendix 2, the Ubolt will generally fail by removing a cone of rock rather than a short cone and some bonding failure, but I can't see much evidence of drilling 'damaging' the rock between the holes. This could certainly be a possibility in fractured quarry rock.

With wider spaced legs, if a uniform curve is made the ring protrudes from the rock (by half the hole spacing) as in the photo above. By making 2 tighter bends the profile can be minimised as below.

Figure 1.7 Typical homemade Ubolt showing grinding, notching, and reduced eye profile. 90 mm embedment and 40 mm spacing.

It is possible to place Ubolts horizontally as runners, and this may make unclipping very unlikely, but they could bend downwards in a big fall.

Welded Eye Bolt

"There have been a number of welded eye bolts on the market but weld failures have always been seen as a problem. One on the market (not in Europe) that I know of is the USHBA bolt made from titanium, in tests by the German Alpine Association (D.A.V.) three out of five broke at the weld at under 10kN. Since writing this Fixe have started producing a bolt with a welded eye, they stamp on them 35kN but there are recorded tests giving lower values though still acceptable for EN959. While a number of these have proved to be reliable there are two areas of concern. The first and main one is the welding, without correct material selection and a very experienced welder this will always be a weak point. The DAV have tested a large number of these (a home-made series) and had shaft failures as low as 50N! A secondary problem can be poor shaft preparation leading to insufficient bonding. Of course a well engineered bolt constructed by trained personnel won't have these problems, the welded eye bolt from Fixe for example being an excellent product" [Bolt Products]

Figure 1.8 Weld failure in 8mm tested ring. Snapped 10 mm ring, snapped by hand force of ~ 10kg with a 150mm shifter.

Figure 1.9 Massive 13 mm rod welded ring with 230 mm embedment. Probably bomber.

Why not put rings in upside down?
At first sight this appears very sensible as there will be no twist applied to the ring (which is the ring's weakness) because the load is applied on the ring bolt axis, and not out at a lever arm of about 30mm. The problem is that the shaft is much weaker where the weld is made (the shaft is cold worked which increases its strength, heat from the welding reduces this strength). Under a modest fall the ring bends downwards and, as it is no longer notched into the rock, it now twists easily. The krab is also further away from the rock which adds to the leverage and bends it down further. This problem would not occur with a forged eye-bolt or ring, as there is no weak point.

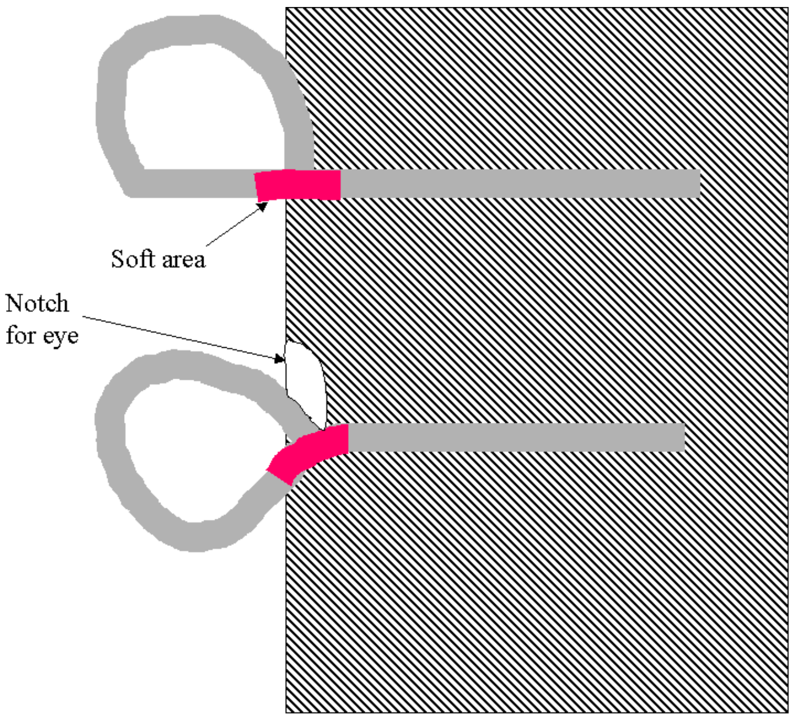


Figure 1.10 Before- eye is sunk into rock to avoid twisting After load, the ring bends down and is no longer sunk so may twist. The weld may also crack

The shaft is also weak around the weld in a conventionally placed ring, but the section of eye notched into the rock supports the ring from bending down.

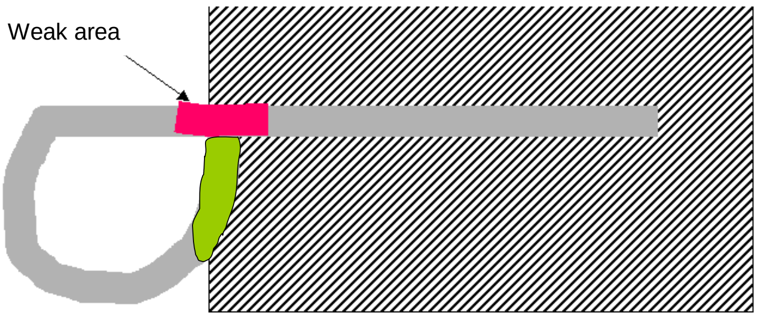


Figure 1.11 Conventional ring, weak area is support from bending down (this ring isn't really set deeply enough into the rock). The eye below the weld (shaded green) should be fully buried in the rock.

Appendix 2 Gluing

This is always messy and expensive, but a good way to make a pair of climbing pants that will last for ever. You need to get a good glue, polyester or the stronger epoxy, know how to mix it correctly, know how to recognise when it is mixed correctly and when it's wrong, take samples, and have well cleaned holes.

Summary

The Glue has to set to work, know what will stop it setting and how to test or recognise this, The Glue has to bond to the shaft, this requires cleaning and some mechanical notching. The glue has to bond to the rock, this requires careful cleaning.

A number of different systems are available:-

Injection

Cartridges are the choice of most climbers but are about three times the price as bulk and the cartridge guns can be very expensive to buy along with the mixing nozzles. A wide range or injection systems are available, all pretty convenient and expensive (about $30 a cartridge, which will do 15 - 25 bolts) if you're placing lots of bolts.

Capsules

Capsules have been used (about a dollar each), these limit the mess a bit, but are hard to get to work reliably, you need a drill bit with a socket welded to it for spinning the bolt, there's probably not enough glue in them to fully bury the welded part of a ring. You should note that there two types of ampoule epoxy glue. One only requires the bolt is rotated to mix the glue thoroughly, the other formulation **must** be rotated at considerable speed to heat the resin and start the cure, naturally totally impractical for climbers.

Problems arise when they are not compatible with the bolt design, most requiring the bolt to be rotated rapidly to mix the glue correctly. Most of the glue contained in ampoules is too liquid for rock, and may not have enough glue in them for some anchors.

Bulk

The cheapest option is a hand mixing set-up using epoxy (about 30c a bolt), but it goes off quickly in warm weather, and is a bit of a fiddle to get in to holes (people have used chopsticks, syringes and things like it with a bit of thin flexible tubing on it). Due to the problems of getting into holes, it's probably not too good in really small holes (ie. 10 mm holes for 8mm U's or rings).

Bulk has the advantage of cheapness and guaranteed mixing quality but mixing and injection into the hole and working time can be problematic For large numbers of anchors it is the best and cheapest way but takes some organising.

Though U's have 2 holes, a lot of glue may be used up in filling the notch for a ring, so the amounts used per anchor are similar. Take rags to clean up the rock around rings, and your hands.

Glue types

Various adhesives derived from the construction industry have been used; polyester, vinylester, epoxy , epoxy acrylate and, while not strictly an adhesive, quick setting cement. Most climbers nowadays are using vinylester/polyester due to its price and convenience, while not so strong as epoxy the mechanical nature of the "gluing" rather than adhesion and rock failure make this not so important as long as the bolt design is adequate.

Styrene Based Polyester

A high quality, rapid curing resin anchor for small to medium sized fixings. Examples used in Australia include Ramset Chemset 101, Hilti xxx ? Powers xxx ?
Polyester is normally used in cartridges with mixing nozzles. The cartridges can be coaxial with the hardener in a central tube surrounded by the resin, or piggy back with one over the other. Both of these systems require purpose built guns.

The mixed glue in the nozzles hardens within a few minutes so the routes must be prepared (drilled and cleaned) and then bolted in one go, carrying spare nozzles is essential. The hardener is generally too thick to be pumped, so this is thinned with styrene monomer (which is the smelly component). When this evaporates, you may not get hardener delivered in the mix, so know what colours the two components are, and keep checking that they are going through the nozzle and into the hole in the right mix. You can get 20 to 30 holes per 380ml cartridge for a glue cost of around $1 per hole,

Epoxy

These appear to have the best adhesion and strength, but are more expensive. Epoxy adhesives are readily available in three forms;- bulk, self mixing cartridge and glass/plastic ampoules. Examples of cartridge epoxy used in Australia include Ramset Chemset 801, Hilti ???. I have used Megapoxy HT (about $100 for 4L which is about $0.10 per hole. It has the advantage that it washes off in metho before it's cured).

The time to cure can be an issue, 12 or 24 hour epoxies mean you can't climb the route the same day, and if you are rebolting you should leave a tag warning people to test or stay off the route.

Successful Gluing.

The main factors are cleanliness, correct mixing, distribution, temperature and glue line.

Cleaning

Obviously the bolt should be clean, but due to the mechanical nature of the interlock in notches this is not as critical as hole cleanliness. The hole should be blown and brushed out several times. There have been plenty of tests done on this and, especially using cartridge glues, dirty holes are found reduce the pull-out strength by up to 90%.Below is a photograph of a test series using various cleaning methods in a concrete block, identical bolts glued in with polyester and axially tested;

Figure 2.1 Top - Hole blown out with blower.10.4kN. Centre - Hole blown out with compressed air at 8 bar. 15.3kN. Bottom - Hole blown, brushed and blown with blower. 34.7kN - From Bolting Products

The correct way is blow, brush out and blow again, with lung power being nowhere as good as a proper pump (as well as keeping you a bit cleaner!). This is hard to do if the rock is basically muddy inside, like much steep Blue Mountains rock. Damp holes are very hard to clean of all of the drill residue and a good idea when applying the glue is to rub the nozzle against the sides of the hole to mix it into the resin. Most studies show a reduction in bond strength with damp holes, the extent varying with the type of glue and glue system.

It is possible to drill some keying side holes in your main hole with a small drill bit if the rock is very compact, smooth, and isn't cleaning up (rarely a problem on sandstone). In most situations this will only be possible for a short distance inside the hole.

Glue viscosity makes a difference, for example a less viscous (more runny) glue should penetrate the pore structure better. The runnier glue will also allow dust in a poorly cleaned hole to mix with the glue. If you put glue and an anchor into an un-cleaned hole, you can pull it out with a thick layer of dust stuck to the glue. This is significant as the modelling shows the weakest point in the system is generally the glue-rock bond. Rubbing the glue against the side of the hole with the applicator helps mix this in (tho' it shouldn't be there to begin with).

Correct mixing

This depends on the mixing nozzles if one is using the normal cartridge system, but a careful eye has to be kept on the nozzles to check they have not got blocked causing the wrong proportions of glue/hardener to be delivered. Check the use-by date before buying cartridge glues as loss of the solvent can give rise to many problems.

With cartridge systems, once you have a usable mixture coming through, you should always squeeze the initial portion of glue into a baggy to use as a test to ensure that the first amount of glue used also complies with the glue hardening/curing test. Squeeze a test sample at the start and at the end of a gluing session or whenever you start a new cartridge. This ensures that the glue is ok if it is uniform throughout the session. If the sample at the start does not set then go looking for the failed glue in ring/U bolt/s and remove and redo.

With ampoules care has to be taken to follow the manufacturers instructions on any necessary rotation required to achieve adequate mixing.

Using bulk epoxy, one has the advantage of being able to control the mixing process exactly and one always has a sample of each batch in a mixing container to check that it is cured. I've noticed that re-using containers makes for faster setting; possibly there are more of the active free radicals that cause the reaction left there.

A final test is to load (fall) or twist/pull test each before releasing the anchors on the public.

Distribution

This means that the glue should contact all the surfaces of both hole and bolt. With injection systems the hole is partially filled with glue from the bottom to prevent air bubbles and the bolt inserted, squeezing the glue up the sides. When bolts are twisted into the glue rather than shoved in there is a better chance that the glue will work into the threading and notches on the surface. Rotating the anchor will help smear glue onto the anchor and sides of the hole, but won't always remove air pockets. This is one failing of the staple as it cannot be rotated and in tests large air bubbles have been found on the shafts with obvious implications for their strength. Buttering the shafts and sides of the holes while using a hand-mixing setup is a bonus.

Drilling the holes just deep enough tends to force the glue up the holes and expel any air-pockets. Using kinked Ubolts can make it (very) hard to pull them out if you think you have a large air bubble.

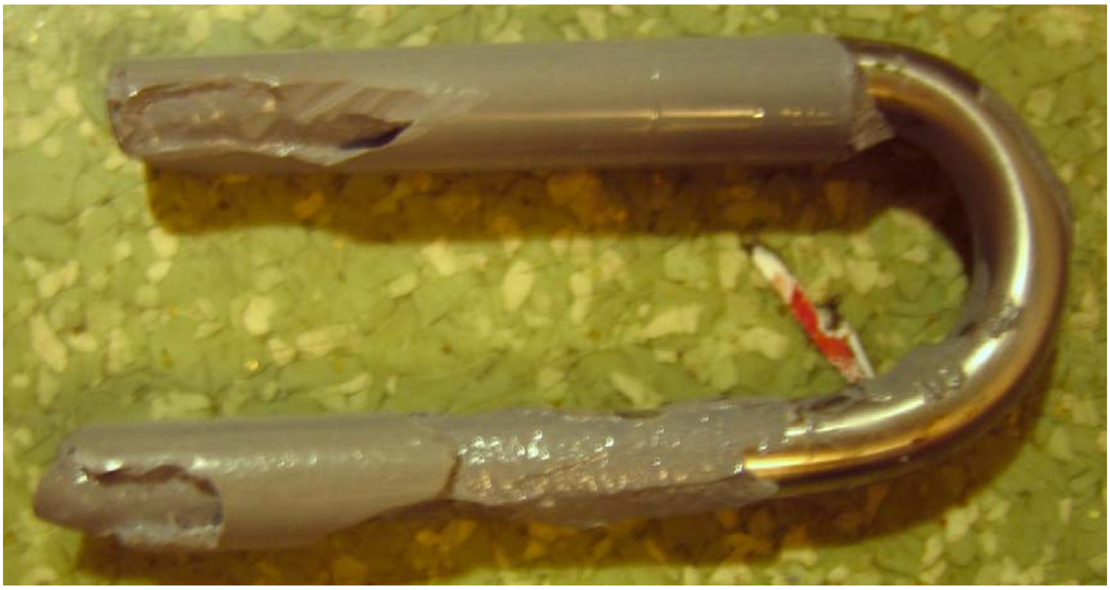


Figure 2.2 Testing of hand mixed epoxy using chopsticks. The ring was set into two12 mm plastic test tubes and typical (top) and worst case (bottom) practices were used (for quality control these were done after a few drinks, in the dark). The test tubes were then removed and the gluing exposed. In practice, one keeps adding glue to sections where a gap appears as you insert the bolt. The glue refused to adhere to insides of the test-tube, unlike when you are putting glue into rock.

Temperature

This is not normally a problem in that most construction adhesives are designed to be used at normal building site temperatures which are the ones at which most climbers are active. So long as one is in the temperature range specified then all is good except that when it is cold full cure can take a very long time. High temperatures mean that working times are short and more mixing nozzles may be required, stay out of the sun, or cool and insulate the glue beforehand. Some people use tropical formulation glues which give you more working time. Thicker glues, or glues that are setting too quickly, will be very thick and may not bond well the rock, particularly if the hole isn’t well cleaned. Neil Monteith mentioned that he had problems using glue on hot days with the glue bonding to the shaft and not to the rock. As pointed out in the section on glue viscosity, temperature can change the thickness of the glue, heat may either make it runnier (before it sets) or thicker (as the working time decreases).

Cure Time

Check the instructions; put a tag on the bolt if you won’t be there to test them, particularly if rebolting a route.

Glue thickness

Many papers describe how glue requires a certain thickness to reduce stress concentrations at the interface between the glue and the rock or anchor (due to very different stiffnesses) typically this is about 1mm thickness. Alternatively, some authors believe that there needs to be a certain thickness of glue to raise the temperature enough to set (glue heats up as it sets, this speeds the reaction further). This seems a bit unlikely as the heat generation in a 1mm film will be small, and rapidly carried away by the anchor.

Offset bolt in a glued hole

This is something people panic about. It may occur with a U when the bars don't line up with the hole perfectly, and with practically all machine bolts and rings. At the worst case the rod might sit against the hole side for its entire length,

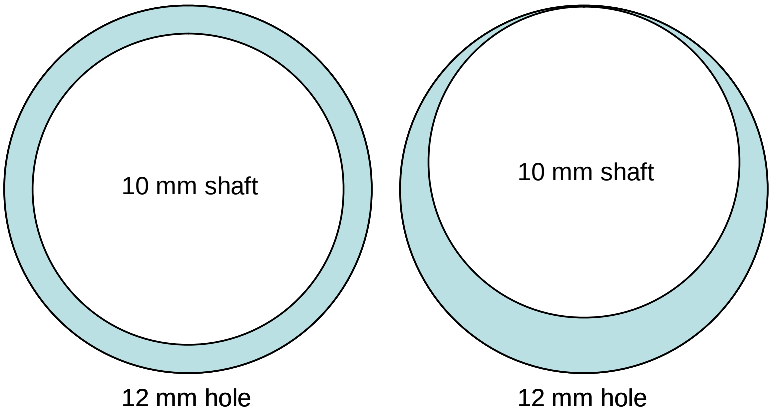


Figure 2.3 Centred hole and off-centre hole

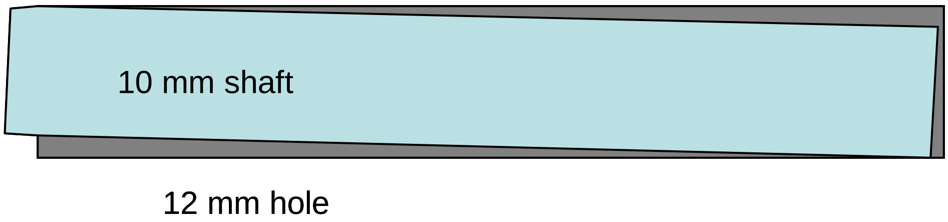


Figure 2.4 Skew shaft

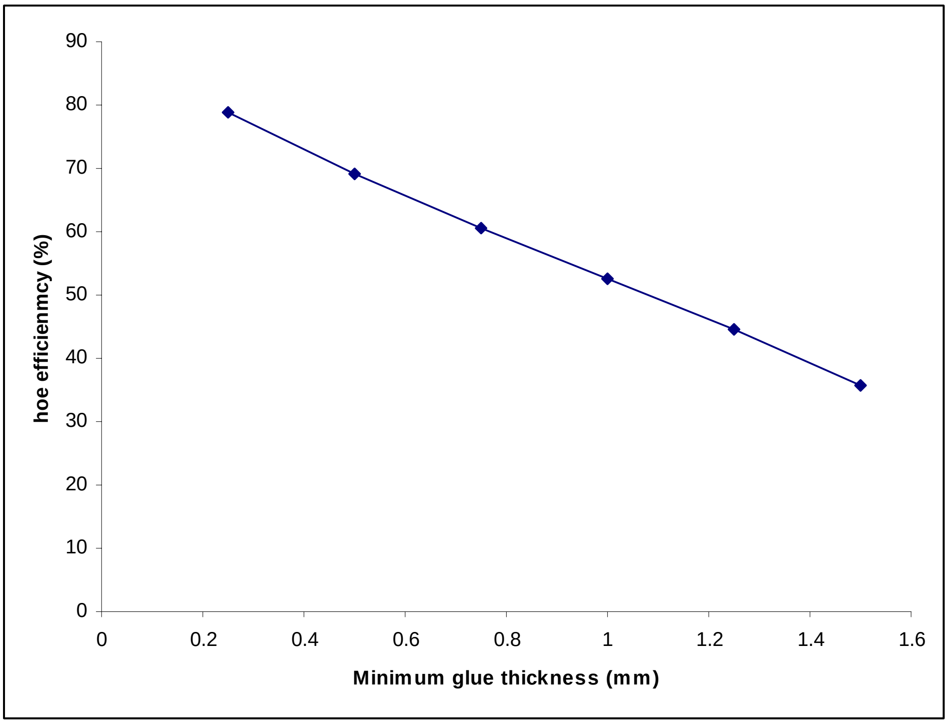


Figure 2.5 Hole efficiency vs minimum glue thickness

In the worst case of a shaft against the side of the hole, if the minimum glue thickness is 0.5mm (unlikely) the efficiency drops to 70% (figure 2.5). For a U bolt this isn't significant (at 80mm depth U vs. 120 mm ring, 70%*80*2 = 112 mm effective length, very close to the 120 mm ring depth anyway. This may be a factor in rings as the ring will generally lie against the side of the hole. But probably not.

Shaft treatments

Steve Hawkshaw's thesis showed typical gluing strengths for plain stainless, lightly threaded (as per the Pircher 8mm bolts, about a 0.3mm thread) notched (about 14 notches, which is about 9% of the surface area), notched and ground, and deeply threaded (with a 10 x 1.25mm thread). Threading is very hard work, even though it's very strong. Notched and ground at about 14kN for an 80mm shaft is just ok.

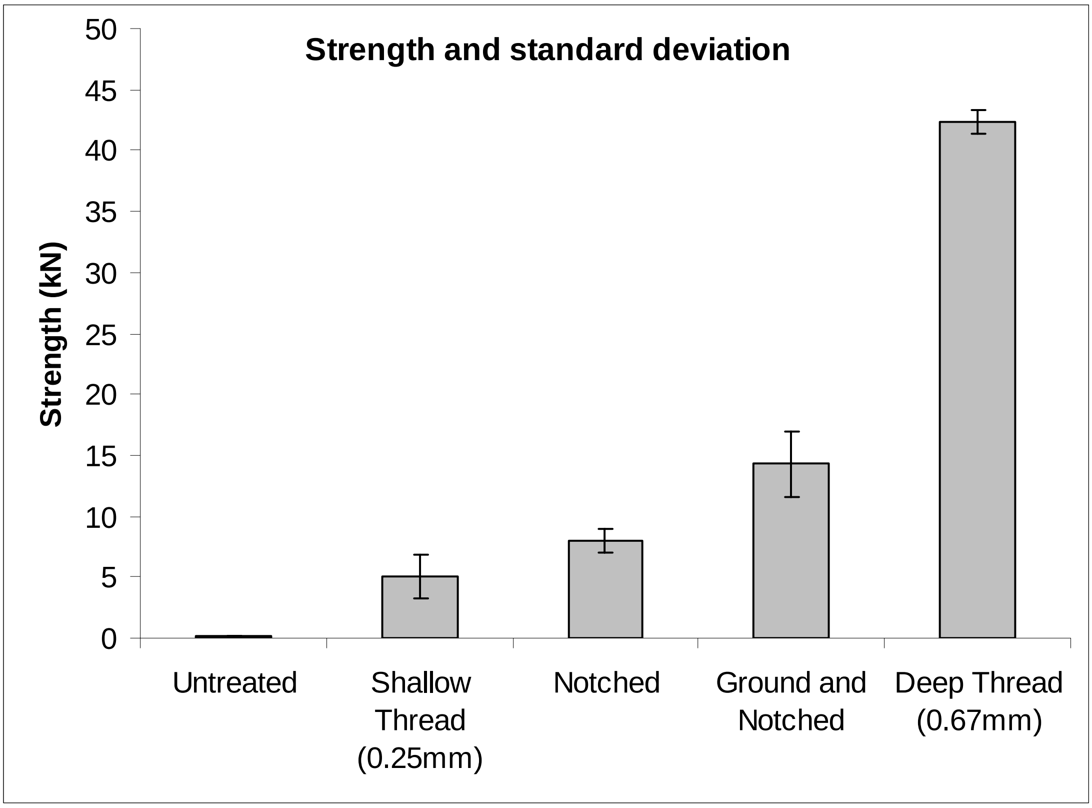


Figure 2.6 Shaft treatment results -taken from Steve's Thesis

There is a simple method of getting good grooving on stainless anchors, without cutting a full depth thread. Put a cut length of bar into a drill, set it on slow speed and fix it (use a vice, or just put your foot on it), then hit it with the angle grinder and make 10 nice notches. As the surface has also been ground it's a bit hard to see, but this gives about 40% of the surface area as notch. Don't make them too deep near the surface of the rock (centre of rod).

Figure 2.7 Rotary notch method

In general the strength of the glue in shear is about the same as the surface to glue bond, so even across a deep notch the glue will tend to fail in a straight line above the surface of the notch. So a deeper notch doesn't give you any better holding power (but, particularly if they coincide on either side of a ring, they can weaken it).

Most anchors tested had notches, generally cut by an angle grinder. These are across the axis of the shaft and are about 3 mm deep at the middle, about 4 mm wide, and some 10 mm long. On Tony Barton's rings there were about 20 of these all up. If we assume that there's no adhesion to untreated shaft that means you have an effective surface area of about 4x10x20 mm^2 = 800 mm^2. On the shaft 10 mm diameter and 100 mm long the total area is pi x 5^2 x 100 = 7853 mm^2. Thus the effective area of bonding on this style is about 10%.

When you use threading you get a big increase in surface area, something like a 9 x 1 mm thread on an 8 mm ring gives a surface area of about 30% (depending on how deep and wide the thread-form is). However, very shallow threading may not allow thick glue to interlock effectively; this is reflected in the poor strength. Even minor wear in the die can rapidly make the threads too shallow to work reliably

Removing glue ins

Drill a small hole(s) along the shaft, bash the ring side to side a couple of times with a good sized hammer to shatter the glue, then bash the ring up and down a dozen times and the ring works its way out.

Testing after gluing

The time-honoured method is to fall repeatedly on every bolt. A parallel method is to take samples of glue in a container or Ziploc plastic bag for later inspection. Another method is to twist test rings and glue in bolts with about 1.5 kg force on a 6” (150 mm) spanner. This tests the glue bond to about 25% of the strength on a ground shaft, which will test if the glue has set, but I’m guessing won’t damage it (something else to be researched). For Ubolts, apply an outwards force of 300kg, or use a lever to achieve the same load (pull 15 kg on a 400 mm screwdriver with the tip inserted 20mm into the Ubolt to get this load)

Appendix 3 An overview of glue-in bolt strength in tension

Summary

The system will fail at the lowest strength mode, this will often be a mixed mode with some rock failure and some glue failure. Longer bolts are better, stronger glues are better. Rock strength isn't as significant as one would think because the glue bond dominates failure.

The simple model presented in the first section of this guide is a massive simplification. A combined failure occurs which shows that anchor length and the weakest bond strength (either glue to rock or glue to anchor) are the most important factors, and that rock strength isn't so significant.

Assuming that the anchor itself doesn't snap, there are 2 contributions to anchor failure, rock failure and bond failure. For a glue in, the rock failure load increases with length, one common formula is that of The American Concrete Institute (ACI) gives the following formula for calculating the load bearing capacity:-

$R = 0{,}32\pi L^2 \sqrt{C}$ Eq 1

Where

R = Rock failure load (N)

C= material compressive strength (N/mm^2)

L = anchor embedment depth (mm)

This equation gives a rapid increase of cone size, and thus pullout strength, with increasing anchor length (figure 3.1). (Other formulae [Cui]) use a lower value of 0.293 rather than the 0.32).

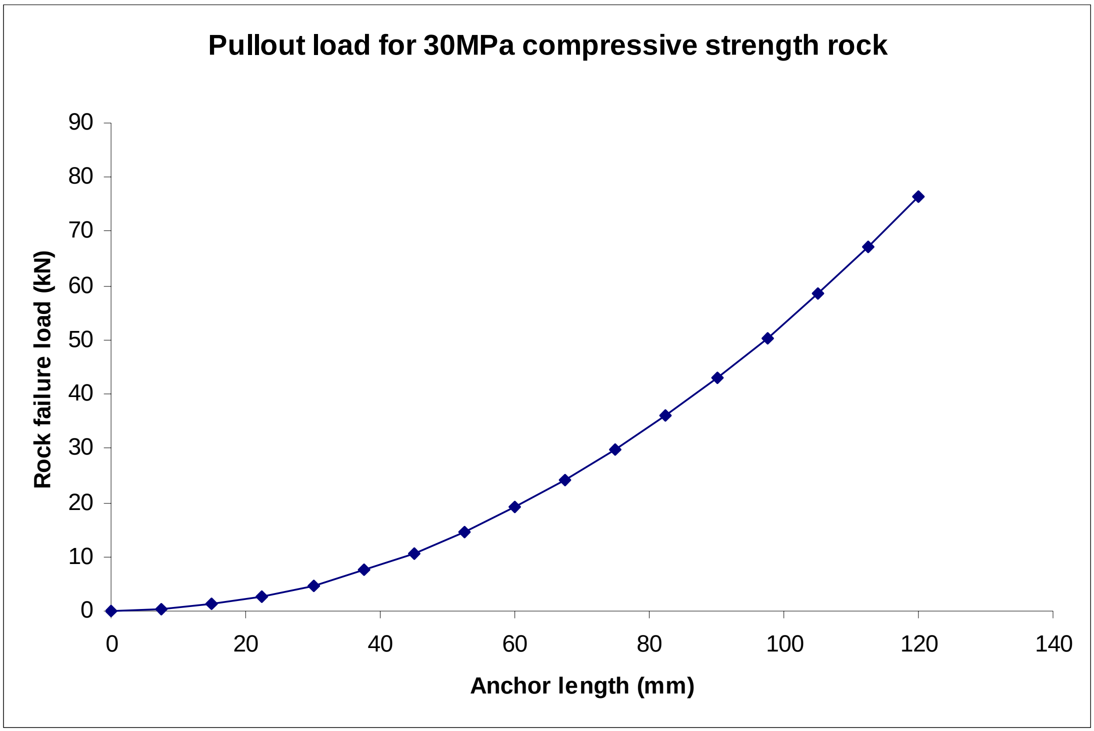


Figure 3.1 Failure load in 27.8 MPa rock or concrete

The rock used in testing for Steve Hawkshaw's thesis was a soft sandstone, the average strength was determined by compressive strength testing as being 27.8 MPa. Interestingly, the tests on 115 mm long rings failed at an average of 20 kN rather than the 70 kN predicted. This discrepancy is explained by looking at a typical tension test result (figure 3.2) showing that full length cone failure doesn't occur (as assumed by equation 1), and that bonding failure occurs also.

Figure 3.2 Rock and bond failure. In this case the depth of the cone is approximately 20mm and the length of bond failure is 100mm. Polyester glue was used, which has about half the strength of epoxy. As we show later, the use of a stronger glue will increase both the length of the failure cone, and also increase the failure load.

In long anchors the bond stresses vary along the shaft [Cook] but for short anchors (less than ~ $35\sqrt{d}$, or 120 mm length where the hole size of 12 mm [2]) this can be ignored and the glue failure load be modelled as simply the bond strength times the surface area, this increases linearly with increasing depth (figure 3.3).

$$G = B\pi DL \qquad \text{Eq 2}$$

Where
G = Glue failure load (N)
B = Bond strength (N/mm^2)
D = Anchor diameter (mm)
L = anchor embedment depth (mm)

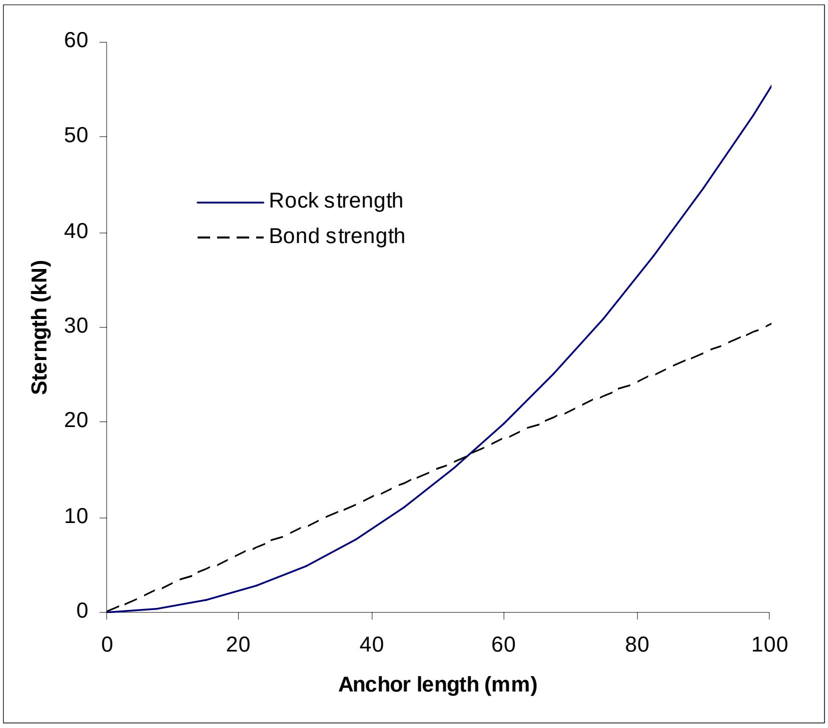


Figure 3.3 Rock failure vs. embedment depth.

When these mechanisms are combined, they compete because as the depth of the failure cone (L_{cone}) increases, the length of bonding decreases. These two functions add to give a curve and the failure will occur at the lowest possible value (figure 3.4).

The strength of the anchor is given by

$F_{total} = B\pi D(L - L_{cone}) + 0{,}32\pi L_{cone}^2 \sqrt{C}$ Eq 3

The depth of the failure cone (L_{cone}) is found taking the derivative of the curve and setting it to zero then

$L_{cone} = BD/(0.64 \sqrt{C})$ Eq 4

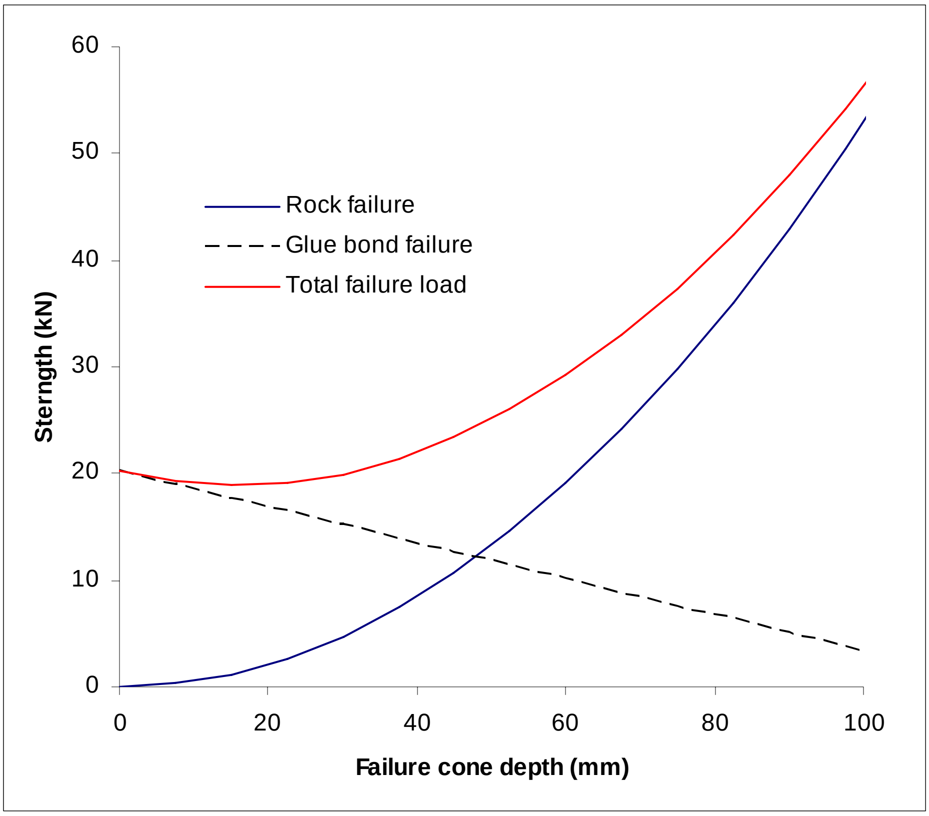


Figure 3.4 Composite failure model predicting failure at a cone depth of 16.7 mm and a load of 19.7 kN

Bond values

The bond strength of 85 mm stainless steel shafts with various surface preparations [2] gave the following values:

	Strength (kN)	% Coverage
As bought	0.185	0
Light threading	5.05	16
Notched	8	7.5
Notched and ground	14.3	7.5 notched and 92.5 ground
Heavy threading	42.3	65

Comparing the notched and heavy threaded values, and constraining the fit to pass through the origin gives a value of 24.5 N/mm^2 (figure 3.5) for interlock into deep notches (> 0.5 mm).

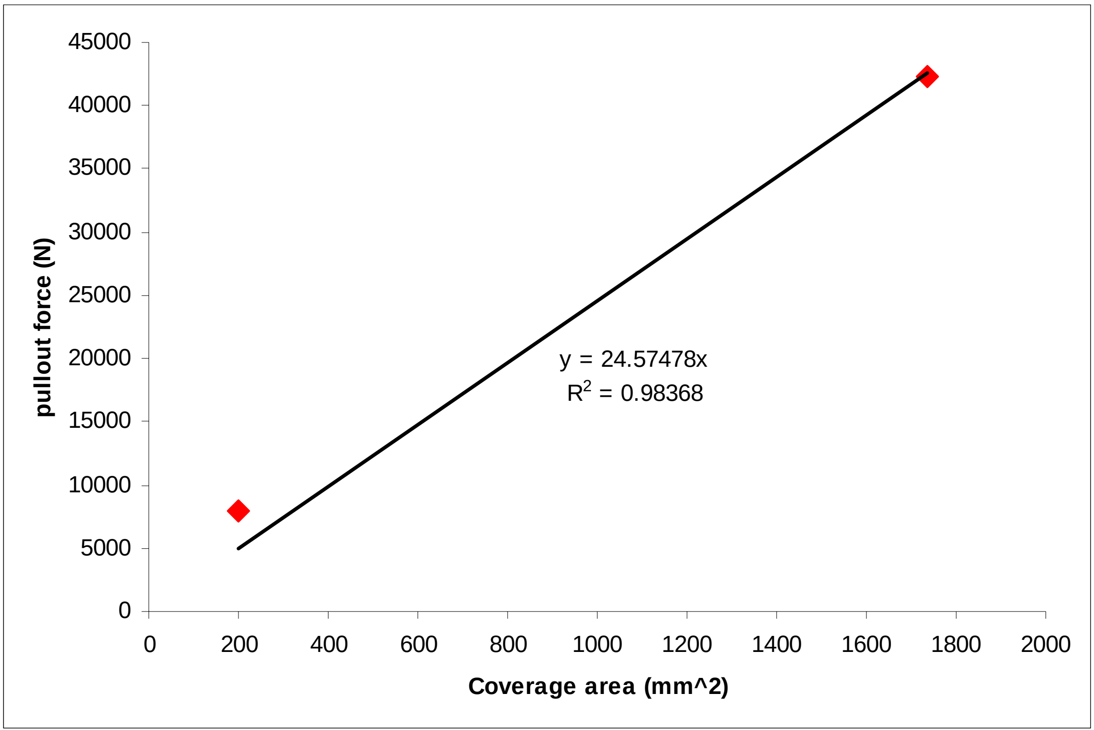


Figure 3.5 Pullout tests

Comparing the ‘notched’ shaft at 8 kN and the ‘notched + ground’ shaft at 14.3 kN, and assuming the grinding covers the other 92.5% of the shaft, we derive a value of 2.55 N/mm^2 for grinding alone. This would give a value of 2.7*10*pi*80=6.4 kN for grinding the shaft alone (or 650 kg) which is too low to rely on alone.

It’s worth noting that, despite all the focus and testing on shaft preparation for gluing, that the failure seen in the soft sandstone testing all either fractured the rock or the glue failure occurred at the glue to rock bond line. The rock to glue bond can be calculated by substituting the hole diameter for the anchor diameter (generally 12mm vs. 10mm).

Using the composite failure model above (Equation 3) for the tests on 10mm rings with 12mm holes, and adjusting the rock bond strength to best fit the data gives a value of 5 N/mm^2 (figure 3.6).

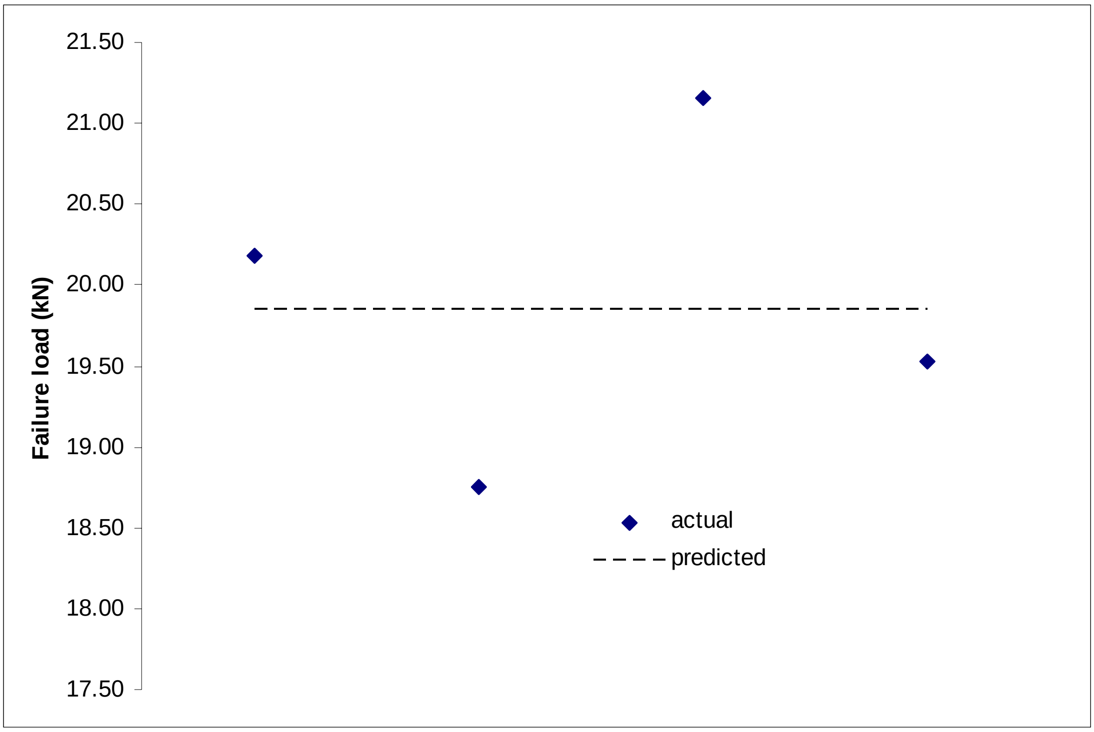


Figure 3.6 Predicted and actual failure loads for 10mm rings showing rock and bond failure

This model works well with single point anchors, but not so well with U-bolts.

With U's, having twice the available bond area tends to produce rock failure with limited bond failure, but at a higher value.

Implications of modelling

This tension model gives some unexpected results for the effects of rock strength and bond strength. The following examples used the same base details, with one varied for each case:-

10 mm shaft in 12 mm hole
Rock bond strength = 5 N/mm^2
Anchor length = 100 mm
Rock compressive strength= 30 MPa

Using the simple cone model (equation 1) not only over-estimates the strength of the anchor, but also implies that doubling the length of the anchor will increase the strength by a factor of 4. In fact, the depth of the failure cone relates to the rock strength and is constant, and any extra anchor length increases the load linearly through the rock-glue bond (figure 3.7). Doubling the anchor length from 60 mm to 120 mm increases the anchor strength from 9.56 to 20.87 kN, a factor of 2.18 (and not a factor of 4).

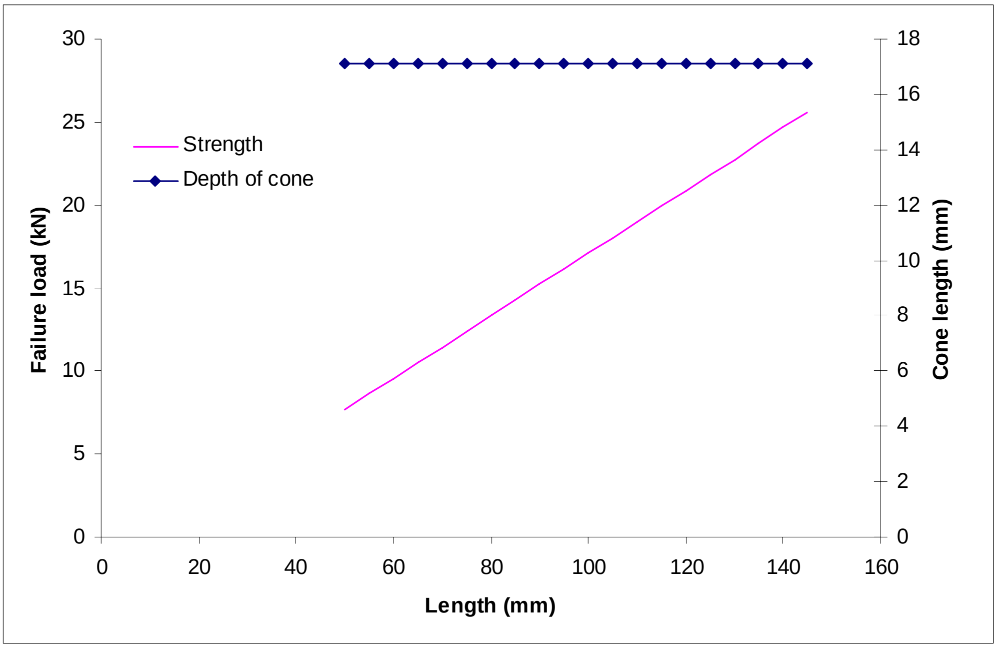


Figure 3.7 Effect of anchor length. 10 mm shaft in 12mm hole, rock-glue bond = 5 N/mm^2, compressive strength = 30 MPa.

Increasing the rock strength gives less of an anchor strength increase than would be expected. Going from a soft Blue mountains type sandstone of perhaps 20MPa strength, to a good quartzite, granite or basalt of > 200MPa would seem to increase the strength by a factor of $\sqrt{200/20} = 3.16$. With the composite model, the length of the failure cone decreases as the rock strength increases, and you only get small increases in failure strength. For this example the strength increase from 20 to 200 MPa rock strength is only a factor of 1.09. Doubling the rock strength from 30 to 60 MPa increases the anchor strength from 17.1 to 17.61 kN, a factor of only 1.03.

For very low rock strength (< 0.88 MPa for a bond strength of 5 n/mm2, and a hole size of 12 mm) the fracture cone length exceeds the shaft length, and the anchor strength will drop rapidly.

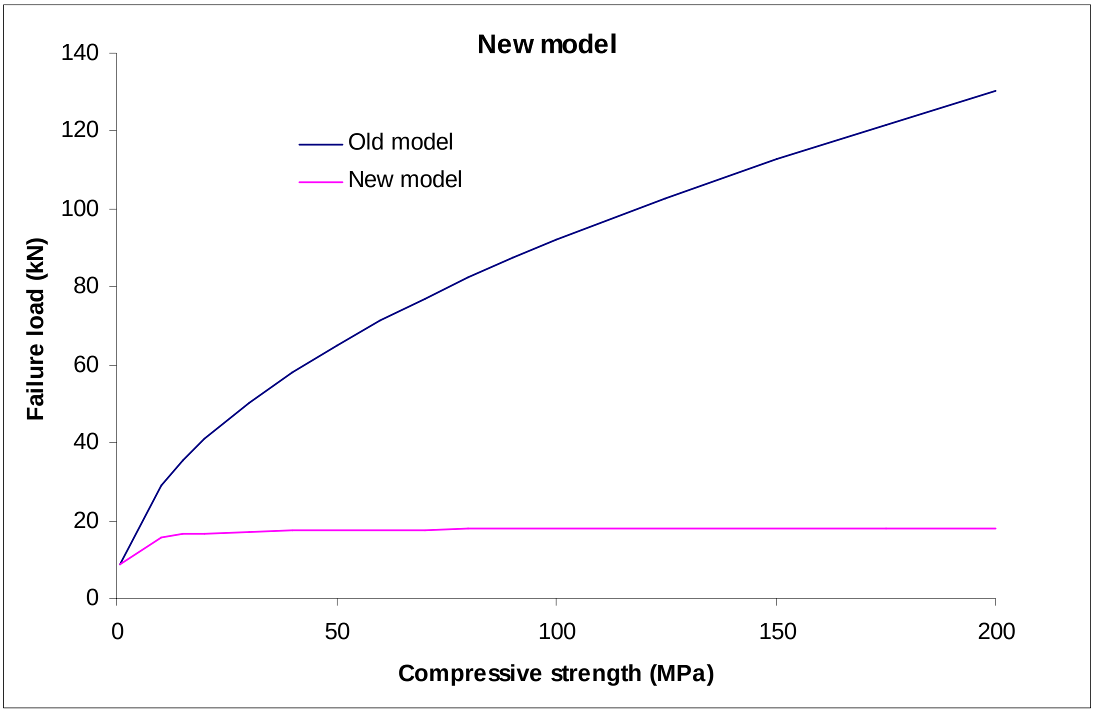


Figure 3.8 Effect of rock strength by old and new model

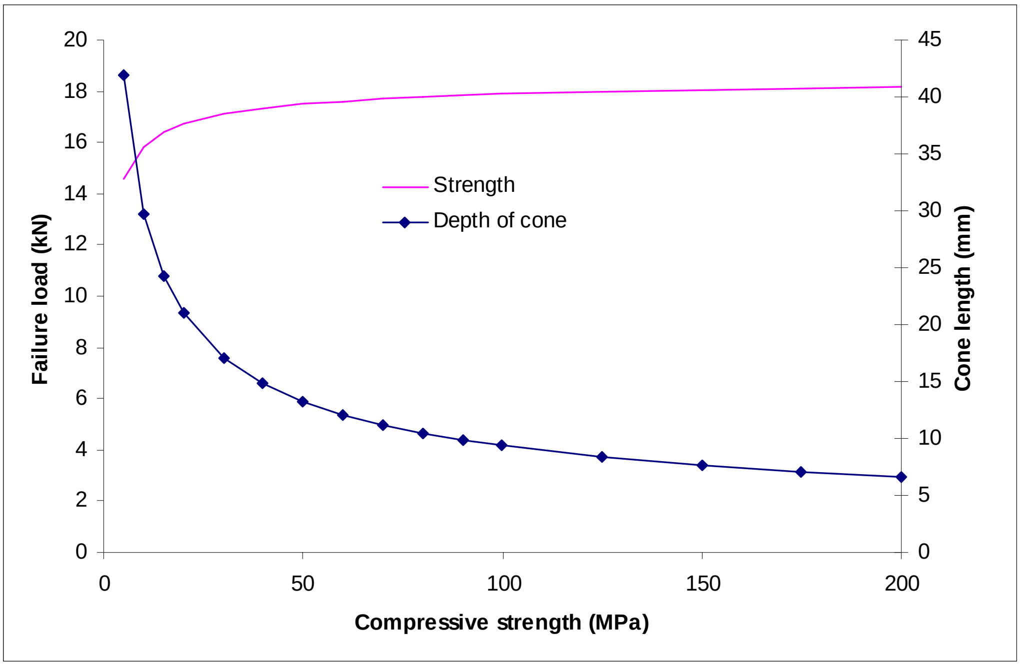


Figure 3.9 Effect of rock strength. 10 mm shaft in 12mm hole, rock-glue bond = 5 N/mm^2 , anchor length = 100 mm.

The factor controlling these failures is the strength of the rock-glue bond (or shaft bond if it is weaker) past the depth of the failure cone. Increasing the strength of this has large improvements in strength. At a certain point, the failure cone depth becomes as long as the anchor length and further strength increases don't occur. Within these bounds, doubling the bond strength from 5to 10 N/mm^2 increases the anchor strength from 17.1 to 30.7 kN, a factor of 1.79.

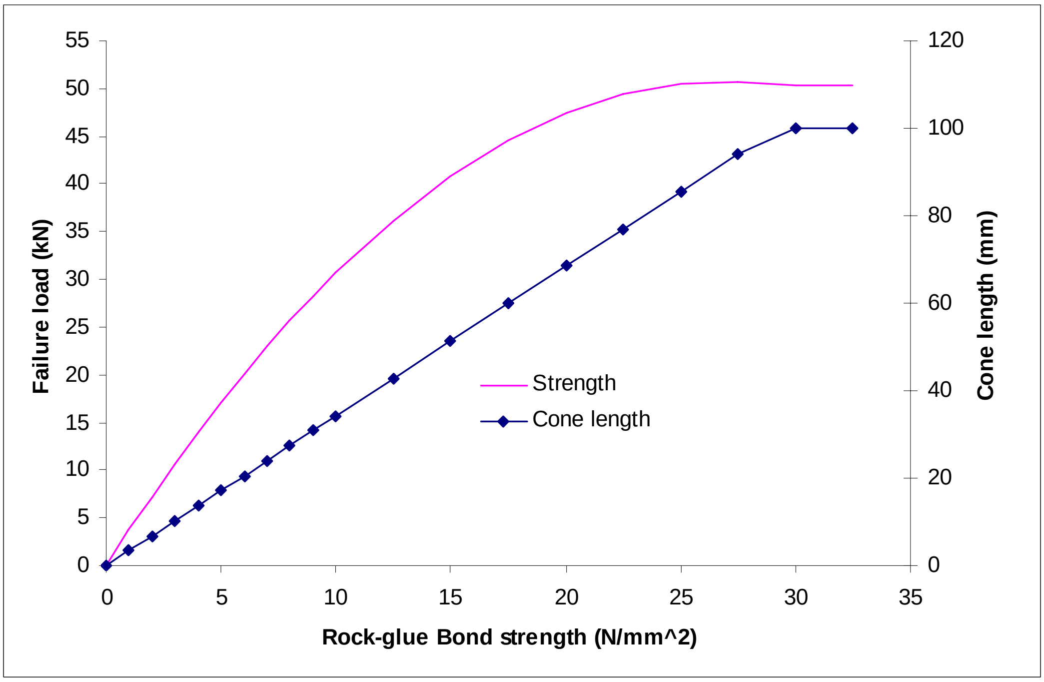


Figure 3.10 Effect of bond strength. 10 mm shaft in 12mm hole, anchor length = 100 mm, compressive strength = 30 MPa. No strength increase is seen once the failure cone length exceeds the shaft length.

These results for tension loading show that the anchor length is very significant, as is the rock-glue bond strength Counter-intuitively, it shows that rock strength has little effect on the bond strength, except in the connection between rock strength and rock-glue bond strength.

Shear testing

Most authors suppose that the tensile failure will be at a lower load than shear. However, when comparing the shear and tension tests, it is seen (figure 3.11) that the Ubolts with 35 and 45 mm spacing have a lower shear strength than tension strength.

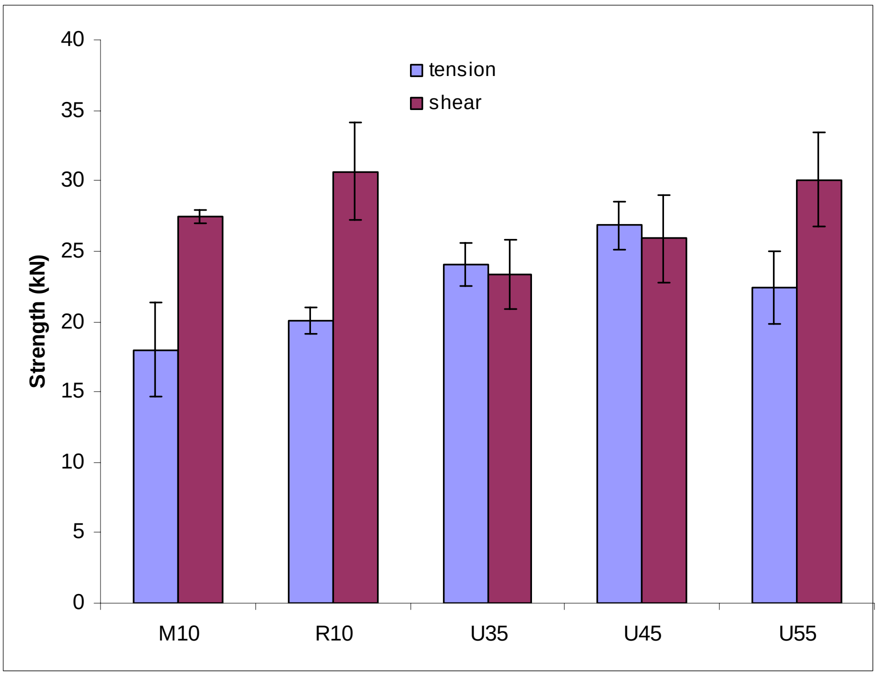


Figure 3.11 Tension and shear data

The failure mode is more complex, with rock crushing under the anchor (figure 2.12), tensile pullout, and (in the block tests) lack of side constraint allowing block splitting, a failure mode which hasn't been seen in anchor failures on cliffs.

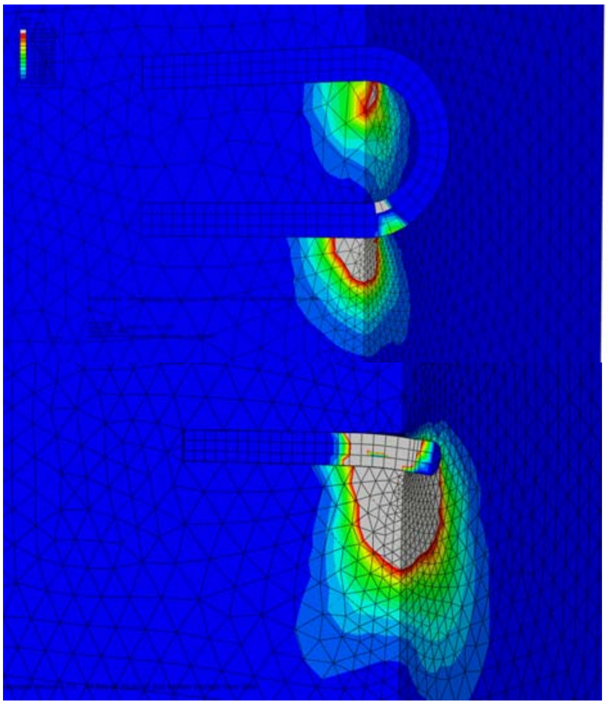


Figure 3.12 Damage evolution (strain > 0.3%) around a Ubolt and a single shaft in soft rock. Half model.

There are significant differences between testing a small 0.5 m block, where there is no side restraint, and testing the same system in a cliff, these are referred to as ‘unconstrained’ and ‘constrained’ tests. Martin Pircher devised a system with improved constraint to better simulate the cliff environment. The rock to be tested is cemented into a ring of steel (figure 3.13). Another option is testing on large boulders or sections of cliff where failure scars will not be an issue.

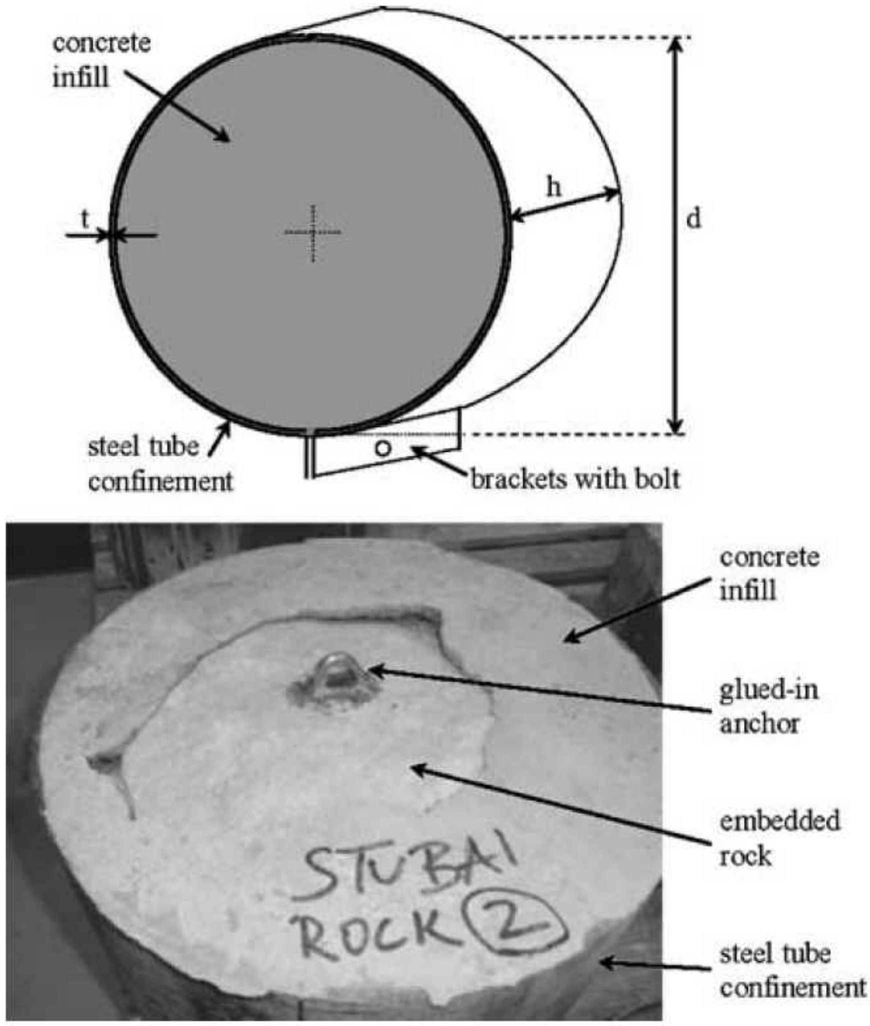


Figure 3.12 Pircher test design.

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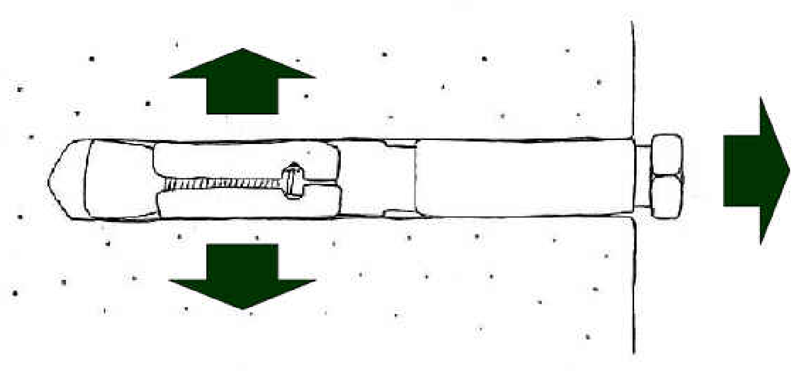
Cui S et. al. (2008) “Adhesive bonded anchorage pullout test to estimate in-place concrete compressive strength” Journal of testing and Evaluation, V36, N6
Hawkshaw (2003) “Strength and reliability of chemically bonded rock climbing anchors in sandstone” Honours Thesis Dept Civil Engineering, The University of Sydney
Cook R A (1993) “Behaviour of chemically bonded anchors” J. Structural Engineering ASCE 199(9), pp 2744-2762
Pircher M (2006) “Testing of rock climbing anchors” Journal of testing and evaluation, V34, N5 Paper IDJTE14117

Appendix 4 Mechanical bolts

Summary - Not acceptable in soft rock.

These haven’t been tested in our local soft rock, no doubt large and long bolts would be acceptable. Large (16 mm or greater) stainless expansion bolts would be pricey, particularly when you add a bracket.. Limited experience shows that fatigue of rock may be an issue. On roofs you can aid or fall on them immediately.

Due to some early failures (with small bolts) under repeated falls these haven’t been used much in the Blue Mountains, but there has been no serious testing of these and can’t currently be recommended as anchors (they are commonly used as temporary bolts when bolting a route).



A mechanical bolt expands, gripping the inside of the bolt hole

Figure 4.1 Loads on a mechanical bolt, from BMC guide to bolts

Rust is more likely to be a problem on bolts with threaded sections and/or lots of parts, unless they’re stainless. The Rawl bolts used at Nowra seem pretty good as they're sealed against outside damp, but if used in rock which is internally wet they may rust up (figure 4.2).

Figure 4.2 Corroded Rawl bolt with evil aluminium hanger. Galvanic corrosion causes rapid corrosion, don’t even think of mixing metals.

Theoretically expansion anchors can’t be used near edges, cracks, or arêtes due to expansion load on the rock, use a chemical anchor.

Mechanical bolts may loosen due to being placed in rock that is too soft. The shaft components in a 12mm Dyna-bolt are a 10 mm shaft and a sleeve, which is not as stiff as a 12mm shaft, thus flexing in poor rock may lead to rock cracking. The outwards load that the cone places on soft rock may crush the rock and cause the anchor to loosen. In areas with particularly weak rock, it may be found that the required torque cannot be applied as the bolts pull through. Under load the bolts can either rip out through the rock, or more commonly, the rock crushes outwards under the pressure of the sleeve and allows it to slide off the end of the bolt. A better choice for this situation are so called "undercut" bolts or glue-ins which will give vastly superior results.

There are lots of different types, the most common are the Rawl type used in the US and at Nowra. Stainless Trubolts are often seen in Victoria. The expansion range can vary, Dynabolt and other sleeve types have their expansion range over the depth of the hole which may help.

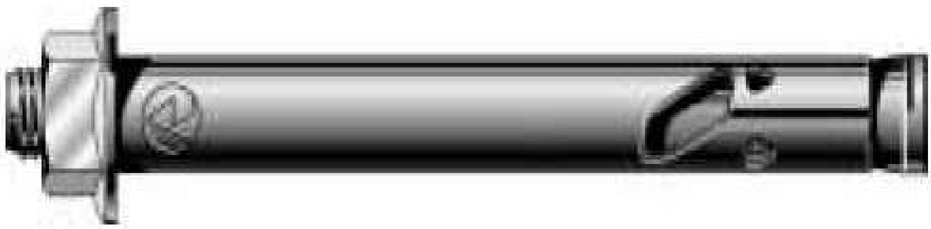


Figure 4.3 Dynabolt – 10 mm diameter is good in strong rock

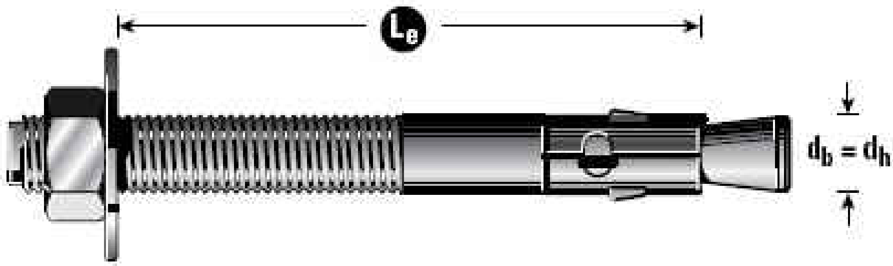


Figure 4.4 Stainless Trubolt – 10 mm diameter is good in strong rock

The sleeve on the Trubolt is permanently sprung out against the rock, and is compressed when it goes into hard rock. In soft rock as the expansion cones are slightly larger than the drilled hole, they shear away the inside of the hole as the bolt is tapped in. This reams the hole and may exceed the expansion range, the bolts probably won’t ever tighten.

A common malady is the nut which does them up and holds on the bracket becomes loose. This normally happens in soft rock, but can occur due to swinging falls in a L to R direction which unloosens the nut.

These are excellent and fast in hard rock, though you need to add a bracket to the cost also. Stainless is preferred, though on limestone coated bolts last for a while. On seacliffs, the many crevices in these multipart bolts may encourage stress corrosion cracking.

Drill an appropriate sized hole (in hard rock, worn bits can drill undersized holes which may not fit the bolt), clean well, insert the anchor and bracket, and tighten to the correct torque. The use of a torque wrench is a good idea, or use a spring balance on the end of a spanner to calculate what the right torque force “feels” like. To stop nuts undoing, (particularly in a right to left traverse, where falls undo the nut) you could use glue or as thread-locking compound on the nut, or centre punch the nut at 3 positions close to the thread.

Appendix 5 Hand drilling

Summary – Hard work

I used to use a standard drill bit of 5/16", and centre drill a 20 mm bar with that, ~ 30 mm deep. Then drill and tap two 6 x 1 mm metric thread into the side of the bar and into the hole.

The drill gets a flat ground on the side of it and that tip is ground to 2 flat chisel points, at about a 70 degree angle, cool the tip frequently as you grind. Grind the back of the drill to about the same taper as the original drill tip, so it will fit in the drilled hole in the holder without loosening. This is good and fast for carrot holes in sandstone (5 minutes per hole from a good stance with a heavy hammer), but you want to carry a spare drill and tools for changing it, as they break easily.

You can do the same with a carbide tipped drill (but don't try to sharpen it!) and it will be a lot more reliable, but will drill~ 40% slower. There are very solid holders which take SDS bits, essential for harder rock, but a bit slow in soft rock.

The bolts I normally use for average rock is a 2.1/2" x 3/8 bolt with an unthreaded shaft at least 15 to 20 mm long. I grind this on 6 side (one to correspond to each flat) till there is a small amount of thread on the corners of the flats at the end of the bolts, and a bit of grinding on the unthreaded shaft, tapering off to nothing.

For very bad rock I've used longer 10 mm bolts, and coachscrews are bomber in very poor rock (but the metal is very weak).

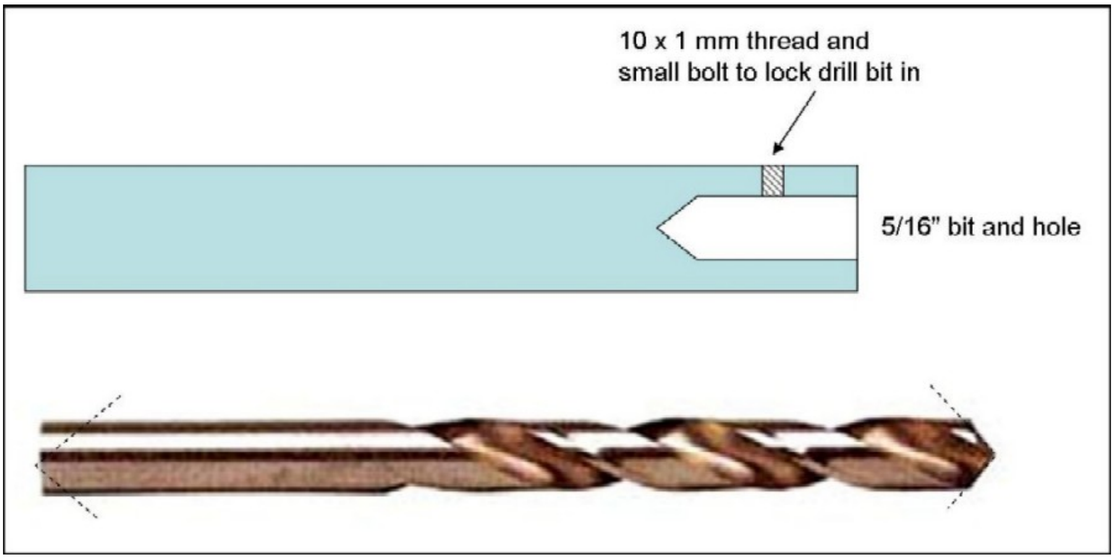


Figure 5.1 hand made drilling rig

Appendix 6 Carrots

Summary – These need skill to get a decent anchor and should be treated with caution. They are weak under an outwards load.

Carrots are a time honoured Australian joke, a fast and cheap way of bolting. They are a machine bolt that has been ground to a taper and pounded into a hole. Compared to regular anchors, they require a degree of skill and familiarity with the rock to get a reasonable product. They often require a removable keyhole bracket that can be a curse to put on, and (with modern skinny biners) can come unclipped.

Carrots fail in a number of ways. In soft rock the most common failure is that it just pulls out under a modest outwards load (the bolt is loose in the hole, caused by over-grinding the bolt or drilling an oversized hole which is easy to do on soft rock). Under big loads the bolt undergoes permanent deformation under large falls and droops which eventually changes the shear force on the bolt to an outwards force (this occurs in hard rock also). Sometimes the rock beneath it is slowly fractured under repeated falls and craters away (much less common). By the way, bolts that stick out miles are generally pretty good (they couldn't be hit in any further), but need the bracket to be kept against the rock (by using an extra wire or wrapping a sling around the bolt) to limit leverage on them. Mild steel bolts will eventually rust till their thickness is insufficient to carry full load, it appears that most of the rusting occurs outside the hole.

Bolts that are almost perfectly flush with the rock may have been hit in with just a few blows and might come out easily. With bash-ins this is due to an oversized hole/small bolt. The bolt sinks in all the way with a hit or two, it may come out as easily. Best to pull it out and start all over again, or use a less heavily filed bolt. In a pinch, a bit of nylon tape or shoe-lace in the hole will temporarily convert this to an overdriven bolt. Hand-drilling makes getting the correct sized hole even more difficult.

In hard rock the most common problems are cracking the rock around them whilst driving them in (under-filed bolt in a hole that's too small), or putting excessive taper on them to get them into a small hole and then they only are holding on the first 10 mm of interference. This loosens with time and the bolt will suddenly come out.

While seconding a visitor up "80 Minute Hour" at the County recently, I got to the first bolt and it came off in my hand. I shook the rope and the next 3 draws, with brackets a-tinkle, came rattling down the rope towards me. I realised that the brackets had all been put on upside down, and asked "Are you belayed to bolts up there?" I had a comfy ledge to cling to while I explained correct clipping technique and we achieved a belay. The climber had used them before, but had a bit of a brain fade on the day.

Carrots are generally ok in terms of strength (and SGABS, stainless glued anchor bolts are bomber). Don't confuse the terror of wiggling on a bracket with concerns about its safety. Despite the intense retro adulation they attract in some circles, the only good thing about them is speed and cost. They are crap in hard solid rock and are only worth the fuss in the Blue Mountains.

Both carrots and SGABS (stainless glued anchor bolts) have the possibility of unclipping as biners are a lot smaller now than in the dark ages, so they will never be an optimal solution. They have a few advantages in being virtually impossible to see, and sometimes cheap and fast to place. Once someone has died by coming unclipped from a bolt they won't be seen as such a great option.

Hand drilling leads to very variable bolts, drilling from crap stances or off skyhooks further enhances the natural duplicity and untrustworthiness of the evil carrot. Be warned

There are a few exciting ways to die with carrots:-

- Pulling them out by leaning out on them, their holding power is variable at best.
- Putting the brackets on upside down is a sure way to feel unfettered and free. The big hole definitely goes down.
- Clipping a biner into a bracket is hard and sometimes flicks the bracket off (like: when you really, really don't want to drop the bracket). Clipping from the top down is easier, but flip the biner over if you clip this way so the gate isn't against the rock.
- Small biners don't obstruct the bolt in the bracket sufficiently to stop the bolt and biners rotating around each other (figure 6.1) in the hole till you're in upside-down bracket situation again. This is more likely with thin biners, or when the bolt sticks out a bit (> 20 mm). You can use a large biner (preferably a screwgate) to stop this happening, or a second biner will often fit in the large hole of the bracket too.
- Wire gates clipped into the bracket are a big no-no (figure 6.2). If the biner flips sideways, the gate is so thin that there is nothing to stop the bracket coming off.
- As with coming unclipped from conventional gear, stiff short draws will make unclipping more likely.

Despite all these negatives, how else can you bolt a 100m route in a morning "for the price of a sausage sandwich" (Greg Child)?

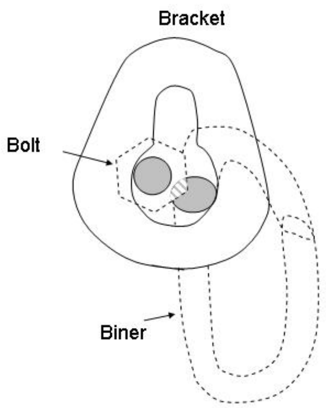


Figure 6.1 If the diameter of bolt + diameter of biner is less than the diameter of the hole in bracket, they can rotate and come unclipped.

Figure 6.2 Wire gate flipped sideways for automatic self soloing. The gates are very weak in this configuration also.

Removing carrots

Try twisting them out with a socket of the right size, a shifter, or a Plumber's Wrench. If they are not budging, hit them where they exit the rock at 4 points with a cold chisel, then they will shear neatly here with a good twist. Don't try to snap them by hitting them backwards and forwards.

Appendix 6 Fatigue

Repeated falls may lead to a lower failure life. Additionally, the rock around the base of the anchor may be damaged by karabiner movement and the integrity slowly eroded (The first Ubolt on Trix Roughly was put in at a steep angle, by me, and the krab is forced into the rock. Rapid wear occurred till a cut down bolt plate was glued over the shaft as a shield).

Martin Pircher performed some testing work on fatigue and found that anchors indeed did fail in fatigue. This anchor in a high strength concrete (probably 50 MPa compressive strength) failed at ~ 40 kN in a single test, at 37 kN after 100 cycles to 25 kN. In weaker concrete (probably 26 MPa compressive strength, or similar to Blue mountains rock) failed at 34 kN in a single test but failed after 98 cycles (figure 6.1) at 25 kN.

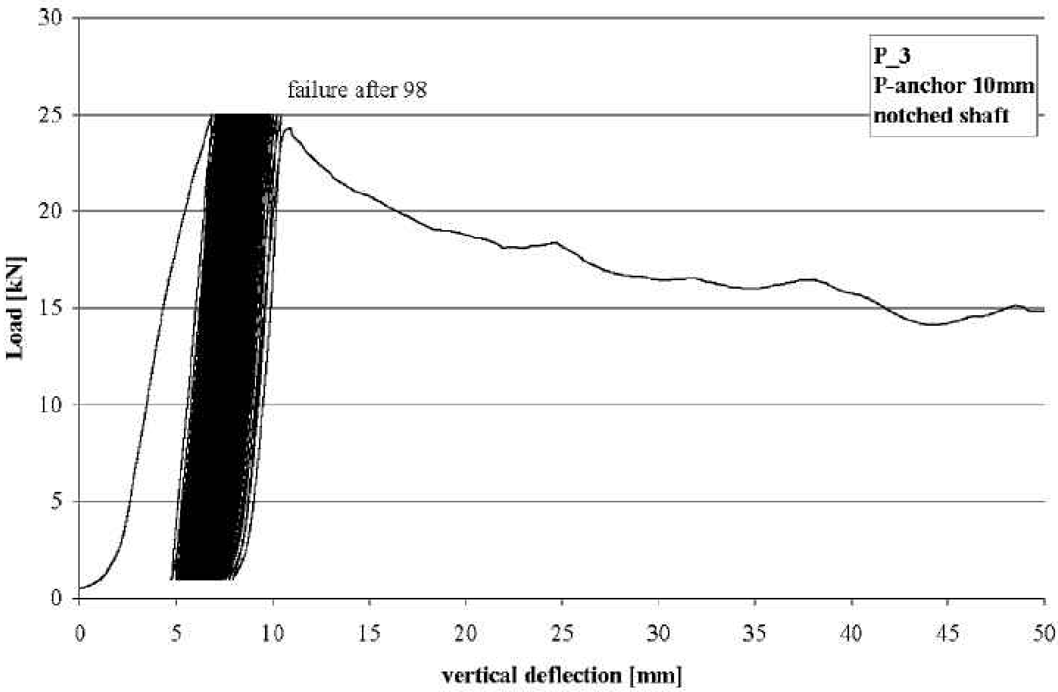


Figure 6.1 Fatigue test from Pircher paper

Pircher M (2006) “Testing of rock climbing anchors” Journal of testing and evaluation, V34, N5 Paper IDJTE14117

Appendix 7 Making U bolts

Material- 10mm or 3/8" (=9.6 mm) stainless, either 316 or 304 grade. This typically comes in 4 m lengths. For most bolts I cut them 250mm long, the depth is about 105 mm or so

The sequence is:-

- Cut to lengths
- De-burr the ends with a grinder (to avoid cutting yourself)
- Degrease (metho, then detergent and rinse) as they come with a greasy coating
- Grind with a bench grinder for about 70 to 90 mm on each end
- Notch- either lay 10 at a time out on a towel that is folded in 3, they make bumps where they sit (put a piece of wood on top and stand on it). Cut 8 to 10 notches and you can rotate them all evenly and get notches all the way round (at 90 degree positions should be fine). Make the notches no deeper than 1mm and not too close to where they will exit the rock (within 10 mm) as both these features can weaken the U, and might lead to cracking while bending.
- OR use a drill to slowly spin the bolt and angle grind notches onto the rod (see figure 3.7), this is a bit slower but more surface area gets notched.
- Threading is best, but without industrial equipment is just too much work (about 5 minutes per shaft, which really adds up for Ubolts) given that the Hawkshaw testing didn't expose any shaft bonding problems
- Bend the U- either use a vice that you've angle ground the edges off (to stop a notch forming which will weaken the ring and wear the rope) or bolt to a convenient corner of the building a 10mm plate with a 12 mm hole drilled in it. Put the rod in and when you start bending the rod will lock in place under force. Put the rod in 90 or so mm, put a length of pipe (0.5m or more) over it and bend. After 4 or 5 U's you'll get the idea and make them evenly.
- A 35 to 45 mm diameter eye is best, too big and they are ugly, too small is hard to make and hard to thread a rope through. A bigger eye is good on belays and rap stations. With wider spaced legs, if a uniform curve is made the ring protrudes from the rock (by half the hole spacing). By making 2 tighter bends the profile can be minimised (figure 7.1), while still allowing a few biners in on a belay.
- The U in this shot was made with a vice, which allows a squarer shape to be achieved, good for getting more biners in without being too ugly. The U has only just enough notches.

Figure 7.1 Typical homemade Ubolt showing grinding, notching, and reduced eye profile

Appendix 8
Testing of anchors
Here is a method of testing anchors to weed out the duds; where glue hasn't set or the worst carrots.

Most experienced bolters can assess their anchors and generally know if there are any problems and also check (fall) on their bolts. I have two possible uses in mind for testing;
1) As a method for new bolters to check their work, especially on rebolting missions. (The average new route has every bolt fallen on, but rebolting is hard to check, and they are often the sort of route that may not get many falls per year)
2) To check the condition of anchors on existing routes.

The concern is to avoid testing at a level that might weaken an otherwise good anchor or allow some time dependent degradation to occur (such as cracking the glue leading to further cracking during falls). Testing should try to remove the small number of faulty anchors (at about 5kN) and not damage the strong 20kN + ones. To achieve testing without damage I suggest testing at some fraction of the strength of a good anchor, probably 10 to 15%, to cover cases of unset glue etc.

Firstly inspect to see if the anchor is loose, if the glue has set, if the rock or glue has cracked.

Bolts
The method I'd like to use for testing bolts is by twisting the anchor. This test method assumes that the shear strength of the glue bond is the same in tension and rotation. An anchor of 10 mm diameter and 100 mm length that would hold 15kN outwards has a shear stress on the glue-to-anchor bond of $F/A=15000/(\pi \times 10 \times 100)=4.77$ N/mm^2. To cause this same shear stress in rotation requires a force of 15kN at the surface, which is 5 mm from the centre. This is a moment of 15000*0.005m = 75 Nm.

Thus the same stress could be caused by a load of 75 N (about 7.7 kg) at the end of a 1 m long bar attached to the bolt (or 15.4 kg at 0.5m etc). This is why twisting removes anchors so well. My guess is that a load which will weed out the rings with bad glue is about 10% of this failure load. This is 7.5Nm, or 0.8 kg at 1m, 1.6 kg at 0.5m, or (more usefully) 5.1 kg at the end of a 150 mm long spanner.

With a carrot we want to avoid yielding the bolt in torsion, while still testing for a weak interference fit. I think the average weak carrot will start to yield at about 30-40 Nm, and testing at 7.5 Nm should avoid damage to these

Rings and Ubolts
With rings the notching will reduce the load on the glue bond. The twist needs to be increased, or else a straight outwards pull could be used. Ubolts can't be twisted in any useful sense, a straight outwards pull is better for these.

For rings and U's I'd use a bar such as a long screwdriver about 40cm long, sit it into the anchor's hole about 5cm and lever out hard, If you pull 20kg at 8:1 leverage it's about 160 kg outwards force which should test adequately (and is about 10% of the UIAA outwards strength of 15kN).

Applying any force as a twist is hard, but pulling straight out is easy. A longer bar would reduce the force proportionally, but is heavier.

Testing time: Poorly set glues are sometimes a tar-like mess and you should hold the tension for 10 seconds to see if there's any creep in the unit.

Expansion bolts
These aren't suitable for soft rock, but after checking the nut is tight, do an outwards pull test in the same manner as for rings and Ubolts