# SNOW ANCHORS FOR BELAYING AND RESCUE

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ABSTRACT: The ability to build a snow anchor and know that it will hold the likely load is an important skill for people working and recreating in snow.

A series of tests carried out in New Zealand by D. Bogie from the Department of Conservation and in California by A. Fortini from the Sierra Madre Search and Rescue Team has shown how strong snow anchors can be, has provided information on why they behave that way, and has shown a number of limitations in the use of both purpose made and improvised snow anchors.

The strength of a snow anchor is dependant on a combination of factors, including: the snows strength in compression and shear; the strength, size and stiffness of the buried object; the angle of placement of the object; the location of attachment to the object and the depth of the bottom of the buried object.

Anyone building a snow anchor needs to be aware of the factors that effect snow strength, be aware of the likely loads for the situation, and know a variety of techniques that will cope with the combinations of snow and loads. The three key things to do when ever possible are to increase snow strength, get anchors deep, and pull from the middle of the buried object. Skis despite their large surface areas make particularly weak anchors if used incorrectly. Two simple tests have been developed to help people with their decisions when building snow anchors: the snowball test and the finger test.

## 1. INTRODUCTION

The strength of a snow anchor is dependant on a combination of factors, including: the snows strength in compression and shear; the strength, size and stiffness of the buried object; the angle of placement of the object; the location of attachment to the object and the depth of the bottom of the buried object. We need to look at each of these and at their effect on each other when looking at anchor systems. We also need to examine how strong anchors need to be for different alpine tasks so that we can build appropriate anchors for those tasks. Testing was done in New Zealand and in California, Utah, and Washington state. Tests were carried out in a variety of snow conditions involved slowly increasing loads using either people pulling on z pulleys or through using a hand operated turfer winch. Load cells were used to record loads at point of failure.

## 2. DEFINITIONS

The following terms used in this document are defined as:-

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Standard sized (New Zealand) stake:- This is 60 cm long and is made of right angle section aluminium (referred to as V throughout the document) with 5 cm wide sides which gives it an overall width of 7 cm. Its area is 0.04 $m^2$. The area is calculated by length times overall width less the area of the points. The surface area of the sides is not taken into account.
Top clip:- Any anchor attached at its top.
Mid Clip:- Any anchor attached at or near its middle.
Upright:- Any anchor put in perpendicular to, or at an angle back from perpendicular to the snow surface.
Horizontal:- Any anchor that is put in horizontally at right angles to the direction of load.

## 3. HOW STRONG DOES AN ANCHOR NEED TO BE?

For rescue work, many practitioners recommend that the anchor be 10 times stronger than the static load. For a rescue sized load of 2 kN this means the total anchor strength should be at least 20 kN. Two by 10 kN anchors or 3 by 7 kN would satisfy these requirements if they were tied together with an equalised system. With climbing things are more complex as loads are often dynamic, and the snow behaves differently under high strain rates. The sort of uses that snow anchors get while climbing makes it unlikely that one would receive the maximum sized fall factor 2 loads. They are mainly used for belaying on moderate angled slopes, belaying over crevasses and abseil anchors. Loads are likely to be in the range of 2 kN to 8 kN.

If a snow anchor is being used to safeguard someone from an avalanche releasing then the load the avalanche is likely to put on someone needs taking into account. For large events forces will be higher than snow anchors can stand but most climbing avalanche accidents typically occur when the climbers set off an avalanche themselves. These avalanches are usually not particularly large and the climbers are normally high in the start zone. If someone is less than a rope length from the top of where an avalanche started the range of loads is likely to be between 2 kN and 13 kN.

For snow safety workers using static cord as a safety line while being belayed in start zones the loads will be similar provided there is no slack in their ropes otherwise loads will be far higher than shown.

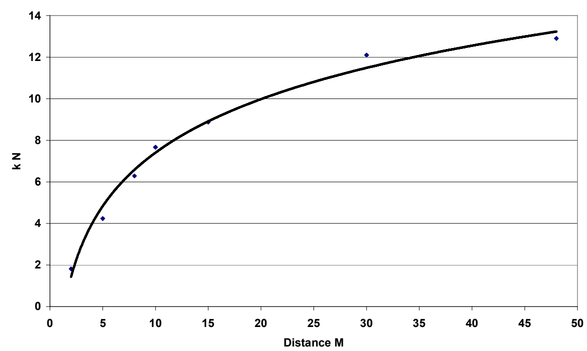


Figure 1: The likely forces on a person held by a rope in an avalanche. The distance in metres is the distance from the crown wall. This example is for a 40 cm slab on a 45$^{o}$ slope. It assumes that the person is in the flowing debris rather than on the surface of the slab, that the person has a surface area of 0.4 m$^2$ and that the debris density starts at 350 kg m$^2$ then drops to 200 kg m$^2$ as it accelerates.

4. SNOW ANCHOR FAILURE

Observations of 250 snow anchor failures by the authors shows that failures occur in four main ways. The equipment fails or the snow fails either in shear or the snow fails in compression or there is a combination of snow failure and equipment failure. The "pure" equipment failures are failures of the attachment systems. Slings or wire strops fail usually in the range of 8 kN to 15 kN. There were a large number of cases of snow stakes bending and either folding and being dragged out of the snow or the attachment pulling out through the stake. Testing in a workshop showed that in order for the attachment to pull out through the stake at the loads being applied, the stake had to bend first. In order for a stake to bend there has to be a compression failure of the snow in front of the stake. Failures of this sort occurred in a range of 7 kN to 16 kN

In compression failure the anchor pulls forward through the snow. Under a steady load this can be a fairly slow movement. The compression strength of a snow anchor is dependent on the compression strength of the snow, the size of the buried object, the stiffness of the buried object and whether the load is evenly spread over the buried object. Failures can either be in a straight line or can be accompanied by rotation of the stake. Compression failures occurred in the range of < 1 kN to around 9 kN

In a shear failure, a stress cone in the snow is formed around the buried object. It has been observed to go out from the sides of the object at approximately 45$^{o}$ and up from the bottom of it at approximately 30$^{o}$. Fortini (2002).

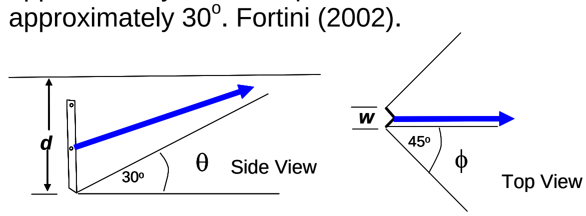


Figure 2: The stress cone. The surface that comes up at 30$^{o}$ is the area of shear. The two surfaces that go out from the anchor at 45$^{o}$ are the tension zones.

When it fails it does so fast and the snow cone and anchor come out of the snow in an explosive manner. The strength of the snow anchor is dependent on the shear strength of the snow on its shear plane and the strength of the snow in tension on its tension surfaces. The size of the stress cone is a lot larger than the buried object. It can be over 50 times the size of the buried object depending on its depth and width. The size of the stress cone can be calculated by working out the surface area of the three surfaces that make it up by using the following formula.

$$A_s = \frac{Wd}{\sin\theta} + \frac{d^2 \tan\phi}{[\tan\theta \sin\theta]} + \frac{d^2}{[\cos\phi \tan\theta]} \qquad [1]$$


Figure 3: Stress cone failures in snow that has been manually compressed do not always show clean shears. Weaknesses obviously exist inside the compacted snow, which mean that the actual shear surface is less than the theoretical area and therefore the strength will also be weaker than the maximum theoretical strength.

Failures under shear are still relatively strong when compared to anchors failing under compression. Shear failures occurred in the range of 8 kN to 19 kN.

An important feature of shear failure is that increasing the depth of an anchor has a far larger effect on the size of the stress cone than increasing its width. When a standard stake is used as an upright anchor it is 7 cm wide. When used as a horizontal anchor it is 60 cm wide. A horizontal mid clip (T-slot) using a 60 cm stake would need to be 52 cm deep to have a bigger stress cone than the same stake in as an upright mid clip.

Tension cracks were observed forming at times with anchors under constant load in strong snow. (ref figure 12) With several of these the entire tension zone was cut by snow saw to see what this did to failures. In those cases the anchor failed in shear at high loads when the load was increased further. This would suggest that the shear plane is the critical determinant of strength and that the tension zones are not adding a lot of extra strength.

From a practical point of view when constructing snow anchors the most important thing is the snow's likely failure in compression. If the snow is strong enough not to fail in compression with the likely loads, then it will have a likely shear failure point that is much higher provided the anchor meets some minimum depth requirements. This can be explained by the size of the shear stress area of the stress cone being far larger than the compression area in front of a stake even though snow is around ten times weaker in shear than in compression.

Compression strength of snow varies hugely from < 1kPa for fist hardness to >1,000 kPa for knife hardness snow. See figure 4. It must be noted that the international snow hardness scale uses a force of 50 newtons. Many practitioners use a force of 10 to 15 newtons when doing snow hardness tests in order to more easily differentiate softer layers. McClung (2006)

| Compression strength | | | | Theoretical Compression strength, if load evenly spread for 60 cm x 7 cm stake with area of 0.04 $m^2$ | |
|---|---|---|---|---|---|
| Hardness | Pa | k Pa Range | | k N Range | |
| fist | 0 - $10^3$ | - | 1 | - | 0.04 |
| 4 finger | $10^3$ - $10^4$ | 1 | 10 | 0.04 | 0.4 |
| 1 finger | $10^4$ - $10^5$ | 10 | 100 | 0.4 | 4 |
| pencil | $10^5$ - $10^6$ | 100 | 1,000 | 4 | 40 |
| knife | > $10^6$ | 1,000 | > 1000 | 40 | >40 |

Figure 4: Theoretical compression strength of upright mid clips using international snow hardness scale.

Snow will fail when compressive stress exceeds compressive strength or when shear stresses exceed shear strength. In weak snow compression failure is the predominant failure mechanism. In strong snow shear failure is the predominant failure mechanism if the load is evenly spread across the anchor. If the load is not spread evenly then this usually means that the compressive stress at the point of greatest load exceeds the compressive strength of the snow and failure occurs in compression. This is the main failure mechanism in upright top clips.

To get a snow anchor that can hold a reasonable load (> 8kN) when the load is spread evenly over the anchor you need snow that has compression strength of at least 200 kPa when using a standard sized stake (0.04 $m^2$) or 270 kPa with a 5 cm wide stake (0.03 $m^2$). These strengths are towards the bottom of pencil hardness snow. A simple snow strength test is the finger test. This is where a gloved finger is pressed as hard as is bearable (approx 100 N) on the snow surface. If it does not go in then this means the snow will be strong enough to build a strong mid clip anchor. If it will just go in then snow strength will be around 200 kPa. As the end of a gloved finger is about 20 mm by 25 mm this is 1/2000 of a $m^2$. A force of 100 N acting on this area is 200 kPa.

We can in some circumstances increase the strength of the snow and therefore the strength of a snow anchor by compacting the snow that we build the anchor in. The useful strength of this compacted snow depends on the speed of bonding. In moist snow this is very rapid. In wet snow some initial bonding usually occurs but bond strength will deteriorate quickly so a snow anchor in wet snow is likely to get weaker the longer it is used. In colder snow < -5$^{o}$ bonding is slow and may not occur fast enough to be of any assistance in making an anchor stronger.

The best test of whether compacting snow will make the anchor stronger is to make a snowball. If squeezing hard will make a solid snowball then you will create strong snow and strong anchors. If the snow crumbles, which occurs with cold snow, it is unlikely to produce stronger snow and may in fact destroy existing bonds and make the snow weaker. If water drips from a snowball then compacting the snow may give it higher density but bonds are likely to be weak and they may break down rapidly.

5. SNOW ANCHOR MATERIALS AND SIZES

It is important that the materials used for a snow anchor and the attachment methods used with them are strong enough to handle the potential loads on them and to maximise the strength of the snow they are in.

The shape of the stake did not seem to matter from the point of view of gaining maximum strength from the snow when used in strong snow. It is possible that the shape of the object could change the angle the stress cone comes out from the object at. Shape may be more of a factor in weaker snow. The theory has been that by placing a V stake point of V to load in all circumstances is that it is more stable when being pulled through the snow and that it can create a bow wave effect that compresses and strengthens the snow in front of it, which makes the anchor stronger. However if it were possible to strengthen the snow by compressing it, then it would be better to do it manually when placing the anchor and know that you have created a stronger anchor than to rely on an unknown amount of compression from a moving stake to do this.

Width and length of the anchor are important for getting the area of snow that gives compression strength or producing the size of the stress cone. The shape and orientation of the section is important for determining the structural strength of the anchor material when under load. In very strong snow when an anchor is pulled from a mid clip the strength of the stake is not a major issue as it is supported by the strength of the snow and the weakest link becomes the strength of the attachment system. In weaker snow the snow does not give this support, so stakes that do not have sufficient stiffness will bend and pull out through the snow. This has been observed at loads of around 7 kN with standard sized stakes.

In hard snow where a top clip is being used stakes failing pulled forward under load as the anchor bent and the snow failed in front of the upper third of the stake. Testing in knife hardness snow showed that the stronger the material used in a snow stake the higher the load it could handle. With the weaker materials and the narrower 5 cm wide stakes the failure was in compression. With the strong wider stakes (7 cm to 10 cm) some shear failures were observed. In order for either of these to happen the upper part of the snowstake has to bend as its lower half is under very little load and is held firmly in the hard snow.


Figure 5: Four upright top clips in knife hardness -10$^{o}$ C snow. 1: Al alloy (6261 T6) failed in shear at 9.4 kN. 2: Softer Al alloy failed in compression at 6.7 kN, 3: Was open part of V to load and failed at 4.4 kN through bending of the stake. 4: MSR coyote that failed in compression at 7.8 kN. Bogie (2005)

The length of a snow stake contributes to its overall area and when used as an upright midclip a longer stake gives a bigger stress cone. In order to gain the benefits of longer stakes the material the stake is made of has to be strong enough to counter the effect of greater leverage. Stakes longer than 60 cm will not make much difference to hard snow top clips unless they are made from materials that are strong enough to offset the effect of higher leverage on them. With mid clip stakes in less than 50 cm the stress cone size starts to get into a range where shear failures start to become more likely at lower loads.

Holes are often drilled into snow stakes in order to provide attachment points, to lighten them and some people advocate it to provide grip. Holes can structurally weaken a stake so care needs to be taken in order to not affect its structural strength. Any holes placed for grip or lightening purposes may in fact reduce a stakes holding power in compression as they potentially reduce the area of snow being compressed.

In order to understand how the stakes were behaving in the snow and to look at the differences between stake materials and stake orientations a series of workshop tests were carried out. This involved pulling on the centre of a stake while the stake was held in place by wire loops half way between the centre and the outside edge. This gave a reasonable representation of a mid clip supported by snow. The stronger combinations of shape with the stronger aluminum alloys failed suddenly at loads over 8 kN. The weaker materials and orientations bent slowly prior to the attachment pulling out. A minimum strength in this test of 8 kN before any bending occurs is recommended for purpose made snow anchors. In weak snow the snow will fail before this force is reached. In strong snow the snow helps support the anchor so anchor strengths greater than 10 kN can be achieved with stakes that meet this requirement.

6. PLACEMENT OF SNOW ANCHORS

Snow anchors can be placed in several different modes, as up right stakes, with attachments at the top (top clips) or in the middle (mid clips) that can be tilted back at different angles. They can also be placed horizontally with attachments in the middle. (T slots)

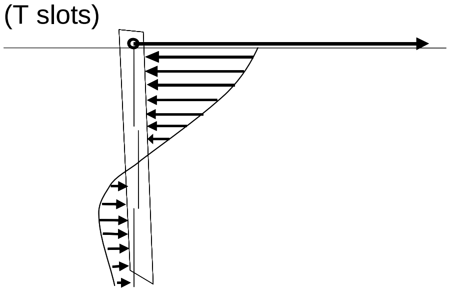

Figure 6: Upright top clip.

One of the most critical things that effects snow anchor performance is where you pull from. An upright top clip is in engineering terms a laterally loaded pile. In the Foundation Engineering Handbook, Winterkorn (1975) it says the following about laterally loaded piles. “Piles are rather slender structural elements, usually vertically inclined, and therefore cannot carry high loads which act perpendicularly to their axis.” If we look at how the load is spread in the snow for an upright top clip in figure 6 then we see that the majority of the load will be on the snow in the upper third of the stake. The actual cross over point from one side to the other will be dependent on the stiffness of the stake and the hardness of the snow. The stronger they are the further down it will be, which will increase the anchor strength as the load is spread over more surface area.

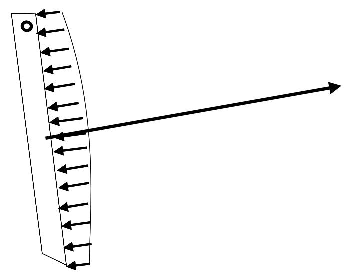

Figure 7: Upright mid clip.

If you pull from the center the load is more evenly spread. If the stake is strong enough it will be even, but if it flexes then there will be higher pressure in the center. Pressure on the snow with a standard sized stake being pulled from the middle with a load of 6 kN is around 150 kPa which is within the range of pencil hardness snow.

During testing in knife hardness snow, some upright top clips were observed to start failing in compression at 6 kN. As knife hardness snow has a strength in compression of at least 1000 kPa this meant that a pressure of greater than 1000 kPa must have been applied to the snow in its upper third in order for this to happen. This is at least six times the pressure the same load would be applying if pulled from the middle.

In knife hard snow conditions (stake needs to be hammered in) top clip anchors gave results for standard stakes in the range of 6 kN to 12 kN. Variations of around 4 kN occurred at times with the same sized stakes in close proximity. The differences appeared to be caused by minor variations in the hardness of the snow that were not detectable by the person placing the stake. As a general rule it would tend to indicate that if an anchor can be placed as a mid clip it should be, as that gives more certainty of a strong anchor than a top clip does. This can be done in most hard snow by cutting a thin slot (< 5 mm wide) with an ice axe pick or snow saw if you are using a stake that has a wire strop. Even if 10 cm or so of the stake is left sticking out of the snow it still gives a far stronger anchor than top clips in the same snow.

The angle a stake is placed in the snow has a different effect depending on snow strength. What increases strength in strong snow has the opposite effect in weak snow.

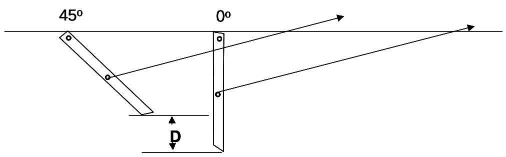


Figure 8: The effect of stake angle on the area of the stress cone ($A_s$). As the angle of a stake is tilted back the depth of its bottom end decreases. The difference in depth (D) means that the size of $A_s$ is significantly reduced.

The depth of the bottom of the upright mid clip has a major effect on the size of a stress cone in stronger snow. The size of the stress cone decreases the further a stake is leaned back. This would weaken the anchor in strong snow. Having a stake as upright as possible in strong snow increases its strength but in weak snow an upright stake will pop up and out of the snow at low loads.

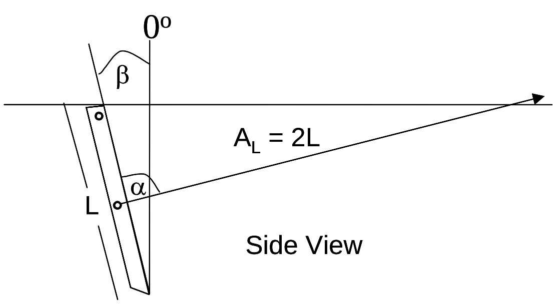


Figure 9: Upright mid clip angles.

In weaker snow where compression is the dominant failure mechanism, leaning the stake back will increase the anchors performance. As the stake moves towards the load as it begins to fail in compression, the angle of the stake influences whether it pulls straight forward, dives or lifts up out of the snow.

- If $\alpha = 90^o$ it pulls in line with the direction of the attachment
- If $\alpha < 90^o$ it produces an upwards component and the anchor will come up
- If $\alpha > 90^o$ it produces a downwards component.

If a stake is leant back $15^o$ from perpendicular to the snow surface with a stake in at its full length and an attachment coming out of the snow at twice the length of the stake ($A_L = 2L$) it will form a right angle where the attachment meets the stake. Lifting up or pulling in line with the attachment will both cause the anchor to fail at relatively low loads. If the anchor pulls in line with the attachment the top of the anchor comes out of the snow and reduces the surface area of snow in the upper half of the stake, which causes it to rotate forward and fail. Tilting the stake back to make angle $\beta$, $45^o$ makes the stake dive down into the snow. Under load they have been observed to travel down slope by several metres and go down into the snow by more than a metre.

Placing mid clip stakes back at $45^o$ in weak snow to encourage diving is not recommended as they can hit harder layers, lay back more then get pulled out at relatively low loads.

If alpha is at $100^o$ between stake and attachment, Braun-Elwert, (2005) this should prevent lifting, minimise excessive diving and would also keep the total depth of the anchor nearly the same as if it were in vertically which maximises the potential size of the stress cone. This angle can be achieved by leaning the stake back by $25^o$ from perpendicular to the surface where the attachment wire or sling is twice the length of the stake, and both the end of the attachment and top of the stake are just at snow surface level. (ref figure 9) Further snow can then be compacted on top of it to get it deeper which makes for a stronger anchor.

Twelve upright midclip stakes were tested at this angle. With those that failed in compression no lifting occurred. Several of the anchors were observed to pull forward and travel down slope maintaining their depth in the snow. In order to allow some room for error when placing a stake it is recommended that when placing upright mid clips that an angle of $30^o$ back from perpendicular is used.

Figure 10: This series of photos of an upright mid clip in at $10^{o}$ back from perpendicular to the snow surface shows it lifting from the snow at around 3 kN. A similar sized stake set back $45^{o}$ pulled down into the snow and failed at around 7 kN when the stake folded in the middle and the wire cable pulled out of it. The snow was cold <-$10^{o}$ C and between pencil and 1 finger in hardness. It was not possible to compress it to make stronger snow.

7. MULTIPLE ANCHORS

When there is a need to produce a stronger anchor than can be built with a single piece of equipment a multiple point anchor can be built. If the pieces of equipment are put in close to each other then an issue occurs with overlapping stress cones. Although combining two tools produces a stress cone larger than one tool, it produces less total shear surface area than two separate anchors would because the stress cones overlap. There is also a potential issue if using an upright ice axe in a multi-tool anchor if it is pulled from the top as this creates uneven load so it is possible that it is not adding to the size of the stress cone, but is instead contributing to the compression strength of the anchor in an inefficient way. It is important with multiple anchors that are likely to fail under compression to set them up so that they do not pull through where another anchor was.

8. T SLOTS

The other mode for placing a snow anchor is horizontally, otherwise known as a T slot or horizontal mid clip. If the snow can be compacted in front of them to produce stronger snow they are very strong anchors. As stress cone size is heavily influenced by depth they would need to be dug nearly as deep as the length of the anchor in order to get greater strength than an upright mid clip that uses the same object. This would require digging and compacting a large volume of snow. In snow that can be strengthened they will take longer to build than an equivalent strength upright mid clip. In weak snow that cannot be compacted to make stronger snow they become the only option for a snow anchor if you do not have an anchor with a wire cable that can be pulled into the snow. In this sort of snow where moving the snow damages snow bonds, a narrow trench needs to be dug for the cord or tape attachment.

9. USING SKIS AS ANCHORS

Although skis have larger surface areas than most of the stakes tested they did not have far higher values. As the load comes on a ski they flex putting higher pressures on the snow near the attachment point. In strong snow used as a mid clip this is not a significant issue.

With top clips this flexibility is a major issue. All of the different combinations of skis used as top clips were weak. This is because the flexing of the skis puts very high loads on the surface snow. The use of skis as top clips is not recommended in any hardness snow because of this feature. Three top clip ski tests produced very low values in the range of 2.2 to 2.9 kN in snow towards the top of pencil hardness range. A top clip stiff stake with a similar surface area produced 4.5 kN in the same snow. If a mid clip had been used in this snow, it would have produced an anchor of > 10 kN.

Figure 11: The photo on the left shows skis in as a X. This failed at 2.2 kN in pencil hardness snow. The photo on the right is two skis in line at the point of failure at 2.8 kN. A noticeable bow has formed in the front ski.

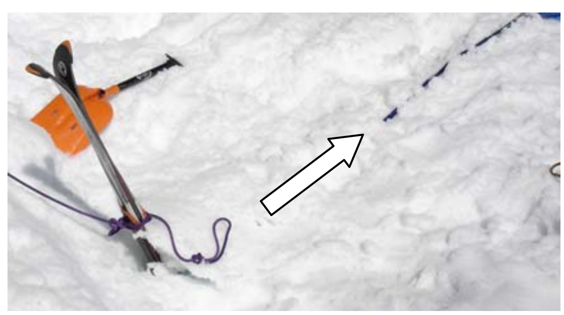

Figure 12: a pair of skis as a mid clip is shown just prior to failure in shear. Note the tension crack. The skis were in to 850 mm and failure occurred at 14.8 kN in pencil hardness snow that had been compacted in front of the skis.

As a mid clip skis can make strong anchors but because of their flexibility they will not be as strong as similar sized stiffer anchors. In snow that can be strengthened through compacting it skis used as upright mid clips with at least half of the ski buried should give a strong anchor. If the snow cannot be strengthened through compaction then skis should be buried as T slots.

## 10. CONCLUSION

The objective when building an anchor in snow is to quickly produce a snow anchor that will not fail under the expected loads. To do this users need to be aware of the factors that effect snow strength, be aware of the likely loads for the situation and know a variety of techniques that will cope with the combinations of snow and loads. Snow anchors do not come under the upper end of the loads they could be subjected to (6 kN to 8 kN) very often so catastrophic failures are infrequent with users. There will however be a number of situations where many people are operating very close to the failure limits of their snow anchors without realising that, particularly if skis are being used as top clips.

The three key things are to increase snow strength, get anchors deep and pull from the middle. If it is not possible to increase snow strength to above 200 kPa then large objects such as skis or large packs/equipment bags need to be buried.

## 10. FURTHER WORK NEEDED

There is a need to do further testing to see whether shape of the anchor affects the size of the stress cone and the differences dynamic loads make. The hypothesis is that dynamic loads that a falling climber could produce should not make much difference in very strong snow but could effect what happens in weaker snow. It is possible that if an anchor is placed so it will pull forward with out lifting that some of the energy of the dynamic load will be absorbed by the compression failure as the anchor moves and that an anchor could hold a higher load than the compression strength of the snow would indicate it should.

## 11. ACKNOWLEDGEMENTS


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