Failure of Snow Anchors

A number of different types of snow anchors are available to climbers and mountain rescuers, including ice axes, pickets, flukes, deadmen, & bollards. All of these anchors rely on the mechanical properties of the snowpack, and factors such as snowpack porosity, density, moisture content, temperature, temperature gradients, slope angle, slope aspect, and time of day can all affect the strength of the snowpack. Consequently, the strength of a particular anchor type can vary significantly from one placement to the next. Furthermore, several of these anchors can be set up in various ways, resulting in even greater variations in the strength.

Snow-pull testing was performed on the various types of snow anchors listed above in various locations in the western United States over several seasons. For each anchor tested the strength was measured, and failure mode was noted. The failure modes of these anchors are described and correlated with features within the snowpack, and recommendations are made as to which anchor types are best suited for use in a snowpack containing weak layers.

With regard to strength, significant variations were seen, even for the same anchor type, buried in the same snowpack, and tested within minutes of eachother. Usually, the anchor types that required the greatest time and effort to set up yielded the greatest strengths (e.g. bollards and deadmen were stronger than pickets). Depending on the needs of the situation (e.g. is speed more important than total strength?), recommendations are made regarding the most suitable anchor type.

About the Presenter:

Art Fortini received his BS degrees in chemistry and chemical engineering from Caltech and his Ph.D. in chemical engineering from the University of Pennsylvania. For the past 13 years he has been working with advanced aerospace materials and is now working as a material scientist. He is currently the Manager of Research & Development for Ultramet, and he has been involved in numerous failure investigations.

He has been mountain climbing for 18 years and he has been with the Sierra Madre Search & Rescue Team for the last 10. Currently he is chairman of SMSR's R&D committee. The snow-anchor data being presented has been collected over the past 4 years in three different states.

Failure Modes of Snow Anchors

By Art Fortini and Joe Morales
Sierra Madre Search & Rescue

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ABSTRACT

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Slow-pull testing was performed on the various types of snow anchors listed above in various locations throughout the western United States over several seasons. For each anchor tested the strength was measured, and the failure mode was noted. The failure modes of these anchors are described and correlated with features within the snowpack, and recommendations are made as to which anchor types are best suited for use in a snowpack containing weak layers.

With regard to strength, significant variations were seen, even for the same hardware, buried in the same snowpack, and tested within minutes of each other. Usually, the anchor type that required the greatest amount of time and effort to set up yielded the greatest strengths (e.g. bollards and deadmen were stronger than pickets). Depending on the needs of the situation (e.g. is speed more important total strength?), recommendations are made regarding the most suitable anchor type.

BACKGROUND

Since 1997 members of the Sierra Madre Search and Rescue Team, in conjunction with members of other mountain rescue teams and commercial equipment manufacturers, have been performing slow-pull testing on various types of snow anchors in different snow conditions. The results given below describe the most commonly observed failure modes, as well as ones that were seen less-commonly.

ANCHOR TYPES

Snow anchors come in many different types and sizes, and the most appropriate anchor will vary from one situation to another. For example, if you fall into a crevasse while crossing a glacier, you're probably don't want your partner to dig a bollard. It's not time efficient, and it will be quite difficult with your weight tugging on his harness. If, on the other hand, you arrive as part of an organized SAR team to perform a recovery from the same crevasse, a bollard may be the anchor of choice.

This paper discusses various types of anchors, which rely upon snow (not ice) as the ultimate supporting structure. These anchors include pickets buried "vertically," pickets buried horizontally, ice axes, flukes, bollards, deadmen, and humans in the self-arrest position.

EFFECTS OF SNOWPACK

Because the load is ultimately being supported by the snowpack, the structure mechanical properties of the snow play a critical role in determining the strength of the anchor. In certain circumstance the presence of a strong, icy layer can decrease the strength of one type of anchor, but increase the strength of another type. Understanding what causes these effects is important if one is to make an informed decision as to which type of anchor is best suited for a given situation.

Most snow anchors operate by attempting to distribute the applied load over a large area of snow. Consequently, the most obvious parameter affecting anchor strength is the compressive strength of the snow in front of the anchor. Snow with a low compressive strength will allow the anchoring hardware to pass through with minimal resistance, but snow with a greater compressive strength will resist such motion.

The shear strength of the snow also plays a role in determining overall anchor strength. When a fluke or a horizontally buried picket fails by heaving or uplift of a large volume of snow, the primary failure is due to shear failure of the snow along the sides and bottom of the displace snow block.

Snow is rarely a homogeneous medium, and layering within the snowpack can have a dramatic impact on the strength of an anchor. "Vertically"-placed pickets rely heavily on the compressive strength of the snowpack **nearest the surface**. Thus, an icy surface is beneficial. A horizontally place picket, by comparison, is unlikely to remain within an icy layer. Once it is loaded to the point where it begins to move and settle, it will tend to follow the path of least resistance and move into a weaker layer. A horizontal picket located in a weak layer is a weak anchor.

A time-honored technique for increasing the strength of a snowpack is to disturb it and allow it to settle. Disturbing the snowpack increases its density by two mechanisms: damaging the individual snow crystals and simple powder settling. In both cases the increase in density results in an increase in the contact area between adjacent crystals. By allowing this configuration to sit undisturbed for a period of time, the grains sinter, and the strength of the snowpack increases.

Other factor that affect the mechanical properties of the snowpack include porosity (or bulk density), moisture content, temperature, and temperature gradients. Not only will these factors affect the strength of the snow, they will also play a role in determining how quickly a disturbed snowpack will settle and regain strength.

Snow, in general, is a highly variable and unpredictable material because of its porosity and because it usually exists at temperatures very close to its melting point. Consider the challenges you would face if trying to design a bridge from steel that was 70% porous and only 10 degrees below its melting point! Because of this variability in the snow, the resulting strengths of anchors built into it will vary tremendously.

As most mountain rescuers know from their studies of avalanche avoidance, there are many factor that affect the strength of a given snowpack. These include its aspect, slope angle, conditions during deposition, time of day, recent weather, temperature within the snowpack, mechanical disturbance (e.g. wind), time since mechanical disturbance, etc. All of these factors also have an effect on the strength of a snow anchor. The primary difference between avalanche forecasting and snow anchor construction is that we, the rescuers, have the ability to strengthen the snow we are about to work with. As described above, we can mechanically disturb the snow pack by taking our skis off and jumping up and down on the desired anchor location. We can then shovel more snow onto the area and repeat the process. This technique will not only improve the strength of low-density, dry snow, it will also mitigate the effects of weak layers within the stomp-affected zone.

SPECIFIC ANCHOR TYPES

Single "vertical" picket

Pickets, like all snow anchors, function by transferring the applied point load from the rope into a load which is distributed over a large area. But because the frontal area of a picket is in the form of a *narrow* plane, it has the potential to cut through the snow more easily than a perfectly square "picket." One can make the analogy of an aerodynamic sports car (narrow picket) versus a sedan (square anchor), both of which have the same frontal area.

If we neglect the effects of aspect ratio (i.e., length-to-width ratio) and assume that the strength of a picket depends *only* on its frontal area, it can be shown that the maximum force that can be applied to a fully-buried, "vertically"-placed picket is given by

$$F = P_{max} WL/2$$

where P^{max} is the pressure at which the snow in front of the picket collapses. P^{max} is equivalent to the compressive strength of the snow. The factor of 2 in the denominator comes from the fact that the picket is loaded in a cantilever fashion, consequently, the pressure applied to the surface of the snowpack is much greater than the pressure applied at the base of the picket. As a result, the strength of the surface of the snowpack is critical in determining the strength of a picket.

Equation 1 assumes that the snowpack if homogeneous. If there is a strong, icy layer near the surface, the strength of the picket will increase dramatically. Conversely, if the surface of the snowpack is weaker than deeper down, the strength will be less. For most snowpacks the temperature at the earth's surface is near 0 °C (32 °F), and the temperature decreases as one approaches the upper surface of the snow. This implies that, more often than not, the strength of a picket will be less than that predicted by Equation 1. In late-season snow, however, the snowpack strength is more homogeneous, and Equation 1 comes closer to predicting reality.

A final caution with pickets has to do with burial depth. If the rope is connected to the picket a few inches *above* the surface of the snow, those few inches dramatically increase the leverage applied to the picket while simultaneously *decreasing* the amount of picket-area pushing against the snow. A single "vertically-placed" picket should be *fully* buried; if the rope is partially buried too, that's even better.

It is perhaps because of these limitations that *Mountaineering, The Freedom of the Hills, 4th edition* states, "Pickets are awkward to carry and provide little security for their weight because of their narrow cross section. They are seldom used today and have been replaced by the snow fluke or deadman anchor." [1]

The failure mode of a "vertically-placed" snow picket generally falls into one of two categories: the picket rotates forward and slides out from the snow, or the picket bends as it rotates forward and pulls out of the snow. In both cases the forward rotation of the picket is undesirable. Once the picket has a slight forward tilt to it, it also has a slight upward component of force trying to slide the picket up and out of the snow.

The tangential sliding force, F^{tan} is given by

$$F^{tan} = F^{app} \sin\theta$$

where F^{app} is the applied force, and theta θ is the complementary angle between load and the picket's axis. ($\theta=0$ if the load is perpendicular to the picket's axis.) Because pickets apply the greatest pressure against the snowpack at the surface, the strength of the snowpack's surface is very important. As it turns out, all snow anchor undergo some motion when a load is first applied. In the case of a "vertically" oriented picket, this means that the picket is going to rotate to a greater or lesser extent as it settles. It is for this reason that most books recommend placing the picket with a backward tilt of 30-45° [2,3]. The intent is to have the picket in a vertical or rearward tilting attitude *after* the load is applied and the picket settles.

Despite these concerns over pickets, they do have a place in the skill set of the proficient of the mountain rescuer. Their most obvious advantage is that they can be placed *easily* in an icy or very dense, hard snowpack - a situation that makes placing a fluke somewhat laborious. In such a snowpack the snow conditions may be very homogeneous, and Equation 1 will be applicable. The factor of 2 in the denominator is still there, but in such a snowpack P^{max} is very large, so F is also large. It is perhaps for these reasons that the next edition of *Mountaineering, The Freedom of the Hills*, states "Pickets work well in snow too firm for flukes, but too soft for ice screws."[2]

Multiple "vertical" pickets

When multiple, identical pickets are arranged in series, the overall strength of the anchor is equal to the number of pickets times the strength of an individual picket. More specifically,

$$F = n\, P^{max}\, WL/2$$

where n is the number of pickets. (This same equation holds true for n pickets placed in parallel and connected with an equalized anchor.) It has been recommended, however, that when multiple pickets are used in series that the individual pickets be only *partially* buried [4]. It can be shown that the maximum load that can be held by a series arrangement of pickets is given by

$$F = n\, P^{max}\, WL/2\ Q1$$

where Q_1 is equal to 1 for fully buried pickets. It can also be shown that the Q_1 values for a series of optimally buried pickets is given by the values shown in Table 1.

n (number of pickets in series)	Q_1 (all pickets fully buried)	Q_1 (each picket buried to optimal depth)	α (optimal fraction of n^{th} picket buried)
1 (rear)	1.00	1.00	1.00
2	1.00	1.06	0.62
3	1.00	1.88	0.74
4 (closest to load)	1.00	1.79	0.83
Total	4.00	5.73	

Thus, in a series of optimally buried pickets, the rearmost picket will be fully buried, the next one only 62% buried, and subsequent pickets each buried slightly more. This arrangement serves to balance the forces on a given picket such that the force of the buried portion against the snow is equal to the load-holding capability afforded by the picket(s) behind it.

Consider two theoretical scenarios. In the first scenario a 3-picket anchor is set up, the burial fractions are 100%, 62%, and 74%, and the Q_1 value for equation 4 is 1.88. If the front-most picket is buried less than 74%, and the applied load progressively increased, anchor failure will start with the buried portion of the lead picket shearing through the snow, and the connection to the rear pickets will act as the fulcrum. With the lead picket removed from the snow, the load will now quickly overwhelm the remaining pickets and sudden, catastrophic failure will occur.

If, on the other hand, the lead picket were buried *more* than 74%, the connector to the rear pickets becomes the weak link. The lead picket will then rotate forward due to the lack of support from behind. In this scenario, all pickets will rotate forward together and fail together, most likely in a very sudden manner.

Given these two scenarios, if you are setting up an anchor and don't have a measuring tape, it is safer to err on the side of burying the picket too deep than not deep enough. If all pickets are fully buried, Q_1 becomes equal to unity, and all pickets are sharing the load evenly (although not optimally).

In reality the snowpack is not perfectly homogeneous, and variations exist in the snowpack, even in the snow between the individual pickets. Pickets also tend to bend, sometime gracefully, and sometimes very suddenly. Both of these factors tend to give the user some notice (albeit very little) that things are about to suddenly go wrong. When the load is initially applied, *all* anchors will tend to settle and move towards the load. This is expected. As the load is progressively increased, the motion of the anchor should slow or stop. If motion starts to increase again, failure is imminent.

One final note on observed picket failures. As noted earlier, pickets typically fail by rotating forward and sliding out of the snowpack. Hence, at the time of failure, they are aimed upward and towards the load, and it is not uncommon for them to become airborne when they fail. Thus, if main anchor failure occurs, flying pickets pose a real risk to rescues as the load shifts to the belay line.

Horizontal Pickets

Like "vertical" pickets, horizontal pickets work by transferring the applied load to the snow via a large frontal area. Unlike "vertical" pickets, which are loaded at the *end* of the picket and create potential rotation problems, horizontally placed pickets are loaded symmetrically (either at the center or at two points equidistant from the center). By eliminating the rotation issue, the load is applied uniformly to the snow, thus all of the picket's surface is fully utilized.

As the name implies, horizontal pickets are pickets that are buried horizontally, rather than vertically. The picket can be girth- or clove-hitched at the center, or the attachment holes can be used for connecting a carabiner. Some pickets some with pre-attached cables. To place a picket horizontally, a T-shaped trench is dug to a minimum depth of 1 foot (deeper is better). The picket is placed at the top of the "T", and the webbing exits via the "trunk" of the "T." Having the webbing exit at a nearly horizontal angle minimizes the upward load on the anchor. As with other anchors, disturbing the snow and allowing it to settle increases the anchor's load-holding capability.

For a series of n horizontal pickets, the maximum force that can be sustained is given by equation 5:

$$F=P^{max}\,WL$$

Compared to Equation 3 for the "vertical" pickets, it is seen that horizontally placed pickets increase the anchor strength by a factor of 2. Field experience and testing confirm that horizontal pickets are roughly twice as strong as their vertical counterparts.

Several failure modes have been observed with horizontally placed pickets, and these include rotation of the picket, cutting of the webbing, contact with a weak layer, local uplifting of the snowpack, and mechanical failure of the carabiner hole.

Rotation of the picket is caused by either an off-center attachment or contact with a hard region by one end of the picket as it initially settles into place when the load is first applied. Once a picket begins to rotate, the frontal area decreases, and its load-holding capability decreases. Failure of the webbing is typically related to the edges of the picket having a small radius of curvature, and failure of the carabiner hole generally indicates exceptionally strong snow.

Contact with a weak layer is a failure mode unique to horizontally placed pickets. Most snowpacks are comprised of layers, and some of the layers will be weaker than others. If the snowpack is generally strong and cohesive, but the anchor is placed into a layer of temperature gradient (TG) snow, the anchor will have little strength. TG snow would be an extreme case, but as the picket moves through the snow, it will tend to follow the path of least resistance. If it encounters a layer weaker than the one it was previously in, it will preferentially remain in the weaker layer.

Heaving and uplifting of the local snowpack is by far the most commonly observed failure mode. In this situation the snow behaves as a uniform and cohesive mass, and the failure is believed to be related to the angle at which the webbing travel through the snow from the anchor to the load. As the angle becomes more vertical, the mass of snow uplifted at failure decreases, as does the overall strength of the anchor.

When horizontal pickets can be used in series, it is important to eliminate slack in the webbing connecting the individual pickets. One recommended technique [5] is to place one picket and have it connected to an unburied picket with the actual webbing that will be used. Use the tethered picket to determine where its trench should be dug, but remember to dig the trench a few inches further away. As the picket rotates about the outstretched tether and into the trench, it will move several inches further away. This should be taken into account when determining the location for digging the second trench.

Ice Axes

In all of the preceding discussions regarding pickets, ice axes could also have been used. Thus, a vertically placed ice axe should be tipped backwards as it will tend to rotate forward when loaded. Because the head of the axe provides more surface area than the top of a picket, extra care should be used to ensure that the head is fully buried. This will provide extra strength.

If buried horizontally, great care should be used. Because the head provides greater resistance to motion through the snow, the axe will tend to rotate, and rotation will decrease the holding power of the axe.

Combination: A Vertical Picket/Axe Combined with a Horizontal Picket/Axe

The use of a horizontally placed ice axe directly in front of a vertically placed axe is a time-honored technique for increasing the strength of the anchor. A similar technique can be used with pickets, and such configurations have been tested. The theory is that the horizontal tool/picket prevents the vertical tool/picket from rotating forward. In reality, this works, but only to a limit. The horizontal instrument indeed does help prevent rotation, but because it is placed so close to the surface (typically ~6" deep), its strength is severely compromised.

The deeper the horizontal instrument is placed, the stronger it becomes, and the fastest increase in strength comes between the surface and a depth of ~1 foot. Thus, if one were to place the horizontal instrument deep enough to provide meaningful purchase, it will render the vertical instrument unnecessary. The second instrument could then be used as a separate anchor.

Recommendations for Pickets ("Vertical" and Horizontal)

- Vertically placed pickets should be angled back and away from the load.
- Wide pickets provide more strength that narrow pickets.
- Long pickets provide more strength than short pickets.
- Soft snow should be compacted and allowed to settle prior to placing pickets.
- Single pickets placed "vertically" should be completely buried.
- For multiple "vertical" pickets placed in series, the rearmost picket should be completely buried, and those closer to the load should be buried for approximately 3/4 of their length.
- Because "vertically" placed pickets typically fail very suddenly and with little warning, a redundant anchor should be used.
- For a given length and frontal area, pickets with a T-shaped cross section are less likely to bend than those with a V-shaped cross section, but the T-shaped pickets will weight ~40% more.

Snow Flukes

Snow fluke operate in a manner almost identical to that of horizontally buried pickets. In practical terms, there are several important differences. The first is that flukes have an aspect ratio closer to unity than pickets, so flukes are much less sensitive to weak layers within the snowpack. It would take a much larger weak layer to have the same effect on a fluke.

For a given frontal area fluke are also much lighter weight than a picket. Because of a picket's large aspect ratio, it is more prone to bending. As a result, manufacturers have been forced to either add a rib (T-shaped cross section) or use V-shaped stock. Both configurations add weight without increasing frontal area.

For a series of n flukes placed in series, the maximum sustainable force is the same as that given in Equation 5. Flukes and horizontally-placed pickets have the same theoretical strength for a given frontal area, and twice the theoretical strength of a "vertical" picket in the same snow.

One characteristic of a fluke is the rake angle: the angle between the fluke and the plane perpendicular to the cables. Most books [1,2,4] recommend that the rake angle be 45°, although [3] recommends 30-40°. Manufacturers determine the rake angle, and fluke with rake angles between 25 and 50° were tested.

The theory for flukes is that as the load increases, the off-perpendicular rake angle will cause the fluke to dig deeper into the snowpack, thus increasing the depth and strength of the placement. In reality, the greater the rake angle, the more upward force the fluke will place on the overlying snowpack. Testing of flukes with different rake angles in the same snowpack has shown that smaller rake angles result in much greater strength per unit frontal area [7,8].

The most commonly observed failure mode was heaving and uplift of the snowpack, which is a behavior that is very similar to that of a horizontally placed picket. Because it is generally easier to bury a fluke than a horizontal picket, because flukes tend to dig themselves down deeper once loaded, and because horizontal pickets are longer than flukes, the character of the uplifted snow is different in the two cases. Whereas the snow uplifted by a fluke tends to be narrower and deeper, that of a picket tends to be shorter and wider. This again suggests that horizontal pickets will be more susceptible to weak layers with the snowpack.

Rake angle also plays a role in propensity to uplift the snow. As the rake angle increases, greater upward force is applied to the snow above the fluke. In testing done in the same snowpack, a 42 in^2 fluke with a 25° rake angle was consistently stronger than a fluke with 82 in^2 of surface area and a 45° rake angle.

A less-commonly seen failure mode is rotation of the fluke until it is coplanar with the surface of the snow. Testing in Southern California produced this failure mode only twice, and both times it took place when the fluke contacted an icy layer as it was being pulled deeper into the snowpack by the applied load. Apparently, the bottom tip of the fluke was unable to penetrate the ice so instead it was deflected horizontally as the top of the fluke continued to be pulled downward and forward. This same phenomenon was also observed in the testing at Mt. Rainier National Park; however, no icy layers were observed in the snowpack. In those tests the snowpack density was extremely high (0.54 g/cm^3) and the flukes either dug themselves in very deep (~2 feet), or the rake angle of the fluke was very large (50°).

For the instances where the flukes dug deep, the inability of the cable, webbing, or carabiner to cut through the snow would tend to increase the vertical component of the force acting on the fluke. This, in turn, would tend to cause the fluke to rotate into the horizontal position. For the case of the steep rake angle, the fluke was essentially pre-rotated in the wrong direction. This, combines with high-density snow, which caused additional rotation, was enough to cause complete rotation.

In theory, when a fluke rotates coplanar with the snow surface, its frontal area drops essentially to zero, so one would expect the anchor to have no strength. In reality, this was observed only once. In all other tests the steady-state load dropped to between 1/3 and 2/3 of the peak load. In most cases this amounted to 100-200 lb_f.

Generally speaking, failure of a fluke is a gradual event - what engineers refer to as graceful failure. As the load applied to a fluke increases, the fluke begins to move downward and forward. As the load is increased further, the motion slows and may come to a stop. The first sign of failure is a sudden, but not catastrophic, heaving of the snowpack. In slow-pull testing this often results in a temporary low reading on the dynamometer due to the strain relaxation. As the load is reapplied, it is not uncommon to reach even higher loads before the snowpack heaves again. After the first heaving, however, it would be imprudent for a rescuer to continue increasing the load on that anchor.

Recommendations for Flukes

- Flukes should be buried with a minimum of one foot of snow above the top of the fluke.
- Larger fluke provide greater surface area than smaller flukes, and hence provide greater strength
- The snowpack should be probed with a ski pole or ice axe to determine if icy layers are present.
- The snowpack should be compressed and allowed to settle before a fluke is placed.
- Despite what mountaineering texts say, smaller rake angles (25°) yielded greater strength per unit surface area than larger rake angles. Manufacturers should take note of this.
- When multiple flukes are used together, they should be placed side by side, not in series. If used in series, the rear fluke can potentially move into the wake created by the first fluke.

Bollards

A bollard is a mushroom-shaped pillar of snow that is created by digging a teardrop-shaped trench in the snow. Generally speaking, the strength of a bollard increases with size and increasing snow strength.

The most commonly feared failure mode of a bollard is an unpadded rope cutting through the mushroom stem; however, shear failure of the stem due to the presence of a weak layer is also a possibility. In the testing done to date 3 bollards were tested, and they all tested to over 1000 lb_f without failing. Two were tested without padding between the rope and the stem, and in one case, the rope began to cut in very, very slowly. In the other case, a late season snowpack on Mt. Rainier, the unpadded rope didn't begin cutting into the stem until it was loaded to 2300 lb_f. At that point the rope began to slowly cut into the uppermost "corners" of the bollard where the normal force between the rope and the stem would be greatest.

Shear failure of the stem was also never observed in the testing done to date; however, if a Rutschblock test indicates the presence of a weak layer, this becomes a very real possibility. The shear forces generated in a bollard can easily exceed those generated by a bouncing skier. Of course, this weak layer would have to be between the rope and the base of the stem for it to most effectively manifest itself. Consequently, the rope should always be placed as close to the ground as possible with a bollard. Furthermore, because the cross section of the snowpack is made visible when digging the bollard, it should be examined.

Deadman Anchors

A deadman anchor is any tied off object that can be buried in the snow. Examples include packs, stuff sacks filled with snow, skis, tree branches, etc. The fluke is an example of a lightweight deadman, as is a horizontally-placed picket. Generally speaking, the strength of a deadman increased with increasing frontal area and with increasing depth. Because a buried pack, for example, will generally have a much greater surface area than a typical fluke, deadman anchors tend to be very strong.

In testing done to date, only three deadmen were tested, and none of them failed due to heaving or uplifting of the snowpack. Furthermore, the anchors showed very little tendency to move or settle as the load was applied. In one case, however, the webbing which was tied around the deadman (a pair of metal edged skis) failed. The failure was sudden and catastrophic.

Thus, the only observed failure mode was failure of the webbing. Depending on what was buried, one could also hypothesize failure occurring due to failure of the deadman (e.g. the buried skis breaks in half) or heaving/uplift of the snowpack. If a narrow object such as a ski is used as the deadman, the presence of a weak layer may also present a failure mode. Rotation of the deadman (e.g. a horizontally buried axe) could also result in failure. Generally speaking, though, deadman anchors are very strong and reliable.

Human Anchors

Occasionally, the snow conditions will justify the use of humans as anchors. This is commonly done while crossing a glacier: if one person falls into a crevasse, the other two people on the rope are expected to be able to arrest his fall. For rescue anchors, humans may also be used, but there are limitations and risks that must be addressed.

The biggest advantage of using humans as anchors is that they can provide feedback on their stability as the load is being applied. They can let the crew chief know when they are approaching their limit, and the crew chief can take appropriate action. This all but prevents sudden, unexpected anchor failure. Human anchors are also very quick to set up.

Another advantage of using humans is that they will work in snow conditions that would otherwise yield a very weak anchor. For example, if the snowpack consists of one or two feet of dry powder over frozen ground, humans can use their boots or crampons to gain solid purchase with their feet - something a picket or fluke will never do.

The biggest disadvantage of human anchors is that it puts the rescuers at risk. If the anchor is overloaded and fails, the load, as well as all of the human anchors, will end up at the bottom. This risk is not something to be taken lightly, and the anticipated loads on the system should be carefully considered before rescuers are put in the loop.

Another disadvantage of a human anchor is that it requires a lot of rescuers. Depending on the nature of the situation, personnel may be better used elsewhere.

A final disadvantage of human anchors is that they are generally not very strong. Humans tested in the self-arrest position were able to hold an average of 500 lb_f (std dev=161).

Two failure modes were noted with human anchors in the self-arrest position. In the first mode, lower back pain was the limiting factor. This was presumable a result of the anchor person using their upper body to transfer a large part of the load from their hips to their ice axe. On average, this took place at a lower load 445 $\pm$ 157 lb_f) than the second failure more.

The second failure mode occurred when the anchor person relied more heavily on their feet. The strengths were generally higher (614 ± 132 lb_f), and the failure mode was fear of being suddenly flipped over backwards. Although testing was always stopped prior to anyone being popped out of the snow, one would expect the failure to be sudden and catastrophic.

GENERAL COMMENTS

Human Error

For any anchor that involves hand-tied webbing (e.g. pickets), verify that the knots are properly tied. In the testing done at Mt. Rainier, this failure mode was observed *twice*! Inspect your gear before you trust someone's life to it. For items such a flukes that come with swaged cables, human error is minimized, but the equipment should still be inspected.

Understanding the System

For virtually all snow anchors, the strength provided by the snow will be less than the strength of the equipment that we bury. Consequently, the key to building a strong snow anchor requires 2 things: knowing and understanding the structure of the snowpack and knowing the mechanics of the hardware we install in the snow.

Understanding the structure of the snow pack will allow the rescuer to decide which type of anchor will best meet his needs. If there are alternating icy layers and weak layers present, both flukes and horizontal pickets will be severely compromised. In this case "vertical" pickets would be the anchor of choice - especially if there is an icy layer near the surface. ("Vertical" pickets apply the greatest load at the surface; hence an icy top layer will provide added strength.)

Alternatively, the rescuer could strengthen the snowpack by removing his skis, stomping down the snow in the area of the anchor (as well as the area between the anchor and the load), and allowing the snowpack to settle. This will break up and/or remove the layers and make the snowpack more homogeneous. After this treatment, flukes and horizontal pickets would become the anchors of choice.

As for mechanics of the anchors, this applies primarily to pickets and ice axes. In a homogeneous snow pack, a horizontally buried instrument will provide roughly twice the strength of its "vertically"-placed counterpart. In a layered snowpack, however, being able to avoid layers with a vertical placement may be the preferred alternative.

Tradeoffs

While strength is typically the first property that one looks for in a snow anchor, it is not always the most important. Certainly a minimum strength requirement exists for any anchor, but building the strongest possible anchor isn't always the preferred alternative. There are times when other factors such as speed factor into the equation (e.g. pulling your partner out of a crevasse). Tradeoff will always exist, and it is up to the rescuer to balance the conflicting needs and requirements into a system that achieves the desired goals.

In terms of strength, bollards and deadmen are, on average, the strongest anchor for a given snowpack. Flukes and horizontal pickets are a distant second, but generally sufficient for most applications. "Vertical" pickets and ice axes usually come in last, especially in a homogeneous snowpack.

In terms of speed and ease of construction, the order is reversed. "Vertical" pickets and ice axes are by far the fastest anchor to set up. Fluke take slightly longer to set up, and horizontal pickets take longer yet. Bollards and deadmen, by far, take the most amount of time and effort to set up.

Other considerations to take into consideration are sensitivity to layering within the snowpack and gracefulness of failure. Because these authors have never witnessed a bollard or fluke fail, their gracefulness of failure can not be assessed. (Gracefulness of failure should not be confused with strength!) Of the anchors where failures were witnessed repeatedly, flukes generally had the most graceful failure mode, and frequently announced when the snowpack was starting to weaken. Horizontal pickets were almost as graceful, but tended to give less warning. "Vertical" pickets and ice axes had the most sudden and catastrophic failure modes. Usually, there was no warning before the anchor failed and the hardware became airborne.

If the rescuer is not going to modify and strengthen the snowpack by compressing it, he should at least probe it with a ski pole to determine if layers are present. If neither of these precautions is taken, prudence indicates that the presence of weak layers should be assumed. In terms of undesirable sensitivity to layers, the horizontal picket comes in last place because of its narrow cross section. Fluke are somewhat less sensitive to weak layers, but not much. "Vertical" pickets and axes provide much less sensitivity to weak layer because they make use of a much thicker column of snow. Bollards are even less sensitive, but if a weak layer exists between the level of the rope and the base of the stem, this may not be true. Deadmen, because the mere act of digging and refilling the hole disturbs the snow, are the least sensitive to layering.

Measure Values

The attached spreadsheet summarizes the results of all of the anchor tests done to date, and it is the intent of the authors to make this spreadsheet available through the MRA web site. The following tables summarize the strength data and are sorted by anchor type. Because the strengths measured at Mt. Rainier National Park were statistically different from the rest of the data, they are treated separately. These differences are due to differences in the snow, not the hardware.

Table 1. Picket strengths (lb_f)

	CA & UT		WA	
	"vertical"	horizontal	"vertical"	horizontal
2"-wide, **T**-shaped pickets in packed snow	125-270	250	1300-1490	3315-4000
2"-wide, **V**-shaped pickets in packed snow				680-1820
3"-wide, **T**-shaped pickets in packed snow	310-470	670-1180	1450	2010
3"-wide **V**-shaped pickets in packed snow	210-360	210		
3"-wide **V**-shaped pickets in **unpacked** snow	90-180	190		

Table 2. "Vertical" ice axe strengths (lb_f)

	CA & UT	WA
85-cm axe, "vertically" placed in packed snow	150-220, 690[1]	960
85-cm axe, "vertically" placed in **unpacked** snow	90	
85-cm axe, with **boot-axe belay** in packed snow	360-890	360-650

[1] Axe buried 1-hour prior to test.

Table 3. Fluke strengths (lb_f)

	CA & UT	WA
25 in^2, 45°	100-110	
31 in^2, 50°		510-1330
41 in^2, 35°		1640-1730
42 in^2, 25°	120-610	
54 in^2, angle not measured	460	
83 in^2, 45°	130-310	
Compressive strength of snowpack	3.4 psi @ 45°	37 psi @ 50°
	9.7 psi @ 25°	68 psi @ 35°

Table 4. Bollard & deadman strengths (lb_f)

	CA & UT	WA
Padded Bollard, unpacked snow	>1180	
Unpadded bollard, unpacked snow	1000[1]	>4080
1'x1'x2' deadman 2' deep, packed snow	>950	
5.9'x2.5" deadman (skis) 2' deep, packed snow		4126 2492[2]

1 rope began to slowly cut into stem.
2 webbing failed over ski edge.

Table 5. All strengths (lb_f)

Anchor	Strength ± SD	number of samples
"Vertical" pickets (2'x2")	186±48	7
"Vertical" ice axe (85 cm)	189±35	3
Horizontal picket (2'x2")	248	1
"Vertical" picket (3'x2")	263±118	7
Horizontal picket (3'x2")	357±272	3
Fluke (42 in^2 @ 25°)	454±145	6
Vertical ice axe (85 cm) with hip belay	890±1	2
Deadman (1'x1'x2' pack or 5.9'x2.5" skis)	>950	2
Padded bollard (10'ϕ x 2' deep)	>1000	2

SUMMARY

- Flukes and pickets show large amounts of scatter in their measured strengths, therefore multiple, equalized anchors should be used.
- "Vertical" pickets and ice axes yield the greatest strength when buried completely, but they tend to fail very suddenly and without warning.
- Horizontal pickets are usually stronger than "vertical" pickets.
- Horizontal pickets most commonly fail in a graceful manner by uplifting the local snowpack, but sometimes failure is sudden.
- Multiple flukes should be arranged in parallel, not in series.
- Flukes can be sensitive to icy layers, and a large rake angle aggravates undesirable behavior.
- Flukes most commonly fail in a graceful manner by uplifting the local snowpack, but sometimes failure is sudden.
- Bollards and deadmen were the strongest anchors tested, but require the greatest amount of time and effort to construct.

- The strength of all snow anchors is strongly influenced by the strength and structure of the snowpack.
- Snowpack properties are highly variable, and redundant anchors should be used.

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- The Sierra Madre Search and Rescue Team for providing the equipment for many of these tests, much of which was damaged in the course of testing;
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- Gordon Smith of Seattle Mountain Rescue for organizing the testing sessions at the Utah and Washington MRA meetings;
- Kevin Slotterbeck for providing results of tests performed by SMC; and
- Everyone who pulled on a rope or buried an anchor while the testing was being performed.

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Steady state load (lb)	approx strain (ft)	comments	rake angle
0	1	unpacked, but plowed snow	
0	0	packed	
0	0	packed, sudden failure	
		1 h burial, sudden failure	
0	0	unpacked	
0	0	axe#2 horizontal 6" below surface, suden failure	
	0.5	tipped back 15 degrees	
700-750	2		
700	1	more painful	
0	0	failed by 4"	
575	1	limited by pain, axe started to shift	
653	1	axe tilted and pushed boot	
360	1	limited by pain	
425	1	limited by pain	
0	0.5		45
40	2		45
	1	rotated coplanar with surface	50
	1	rotated coplanar with surface	50
800/150	2	rotated coplanar with surface, start 6" deep, end 2' deep, grac	35
1100/500	3	rotated coplanar with surface, start 6" deep, end 2' deep, grac	35
0	2	sudden failure	25
100	2		25
0	2	in icy layer, lower wire bent above ice, popped out	25
100-200	3		25
		packed snow	25
		packed snow, parallel	25
		unpacked snow, series	25
		settled at 400 lb	
100-200	3		45
0	1	sudden uplift	45
100-200	4	rotated coplanar with ice layer	45
0	1	horizontal, sudden failure	
0	0	horizontal, sudden failure. 6" deep, lifted snow wedge	
		1' deep, snow unpacked, #1 bent 20 deg, 1" webbing failed at #1 clove hitcl	
117-1800		20" deep w/ shallow cable angle; one end lifted to 6" & rotated, graceful	
4000	1	cables initially exited vertically; no failure, no snow heaving	
	4	shallow cable angle, not failure, 18" deep	
1181	0	no failure, long leash trench	
0	2	horizontal	
	0.5	end rotated up & out, snow not stomped	
0	0	packed snow	
0	0	unpacked snow	
2492	0	did not fail, 1" webbing clove hitch cut, sudden	
4126	0	no failure, padded clove hitch	
0	1		
0	1		
0	1		
100	2		
0	1		

LA, SLC strength (psi)	Rainier strength (psi)
4	
4	
	16
	43
	42
	40
11	
5	
12	
9	
15	
13	
3	
3	
2	
4	
5	
14	
35	
75	
83	
38	
16	
9	
28	
3	
3	
14	
23	
8	
11	
6	
9	
8	

0	1	
300	1	1st picket plled out, then ss
	0.5	1st of 2 in series, lifted at 1200 lb, bent 60 degrees, & failed first
1600	1	#1 tipped 50 deg, #2 =35 deg; #1 bent 25 deg, #2 popped, sudden failure
0	2	
0	2.5	burried only 2.5', set for 45 min
	1	2nd of 2 in series, lifted & bent 15 degrees, failed last
?	3.5	graceful 2', then 2 pickets bent 50 degrees
0	1	last picket bent 50 degrees
0	0	unpacked snow
0	0	packed snow, picket bent
0	0	packed snow, series
0	0	unpacked snow, series
0	0	unpacked snow, series
1180	0	padded, did not fail
1000	0	not padded, rope slowly cutting, no failure
		did not fail
4083	1	did not fail, corners began cutting at 2300, 9" cuts at SS
950	0	did not fail
405	0.5	limited by pain
277	1	limited by tensile lowerback pain
277	1	limited by tensile lowerback pain
656	1	limited by tensile lowerback pain and leg strength
707	1	limited by leg strength & impending backflip
481	1	limited by impending backflip

test series	location & date
A	conducted by AF et al ~1997 on Angeles Crest
B	conducted by AF & J. Morales 2/01 on Angeles Crest
C	conducted by AF & Gordon Smith 1/21/01 in Salt Lake City
D	conducted by AF, Gordon Smith, & K. Slotterbeck 6/20/01 a

series D snow densitiy (g/cm3)

0.52
0.47
0.56
0.61
0.57
0.54 = average

tool	test series	test #	# of tools	size	maximum strength (lb)	maximum strength per tool (lb)
axe	B	1	1	85cm	150	150
axe	A	1b	1	85 cm	200	200
axe	A	10b	3	85 cm	650	217
axe	B	27	1	85cm	690	690
axe	A	1a	1	85 cm	90	90
axe	D	3d	2	91 cm	288	144
axe	D	4.2d	1	91 cm	963	963
boot axe	B	12	1	with standing hip belay	890	890
boot axe	B	13	1	with munter on harness	889	889
boot axe	C	1	1	73 cm axe with ankle belay	360	360
boot axe	D	18d	1	91 cm axe w/ crampon	575	575
boot axe	D	19d	1	91 cm axe w/o crampon	653	653
boot axe	D	22d	1	with standing hip belay	360	360
boot axe	D	23d	1	w/ hip belay thru harness biner	425	425
fluke	B	23	1	25 in2, 45 degree angle	108	108
fluke	B	7	1	25 in2, 45 degree angle	99	99
fluke	D	1d	1	31 in2, 50 degree angle	510	510
fluke	D	2d	1	31 in2, 50 degree angle	1325	1325
fluke	D	7d	1	41 in2, 35 degree angle	1733	1733
fluke	D	8d	1	41 in2, 35 degree angle	1638	1638
fluke	B	26	1	42 in2, 25 degree angle	472	472
fluke	B	22	1	42 in2, 25 degree angle	209	209
fluke	B	11	1	42 in2, 25 degree angle	514	514
fluke	B	8	1	42 in2, 25 degree angle	366	366
fluke	A	4b	1	42 in2, 25 degree angle	610	610
fluke	A	7b	2	42 in2, 25 degree angle	1100	550
fluke	A	6a	2	42 in2, 25 degree angle	230	115
fluke	C	2	2	54 in2	920	460
fluke	B	21	1	83 in2, 45 degree angle	242	242
fluke	B	16	1	83 in2, 45 degree angle	133	133
fluke	B	9	1	83 in2, 45 degree angle	309	309
h picket	B	24	1	2'x2" SMC (Joe's)	248	248
h picket	D	5d	1	2'x2" V-section	680	680
h picket	D	13d	2	2'x2" SMC	3314	1657
h picket	D	15d	1	2'x2" SMC (w/ 2 cables)	3619	3619
h picket	D	16d	1	2'x2" SMC (w/ 2 cables)	4000	4000
h picket	D	11d	1	2'x2" V-section	1820	1820
h picket	B	25	1	3'x2" SMC (Joe's)	1181	1181
h picket	B	20	1	3'x2" SMC (Joe's)	671	671
h picket	D	9d	1	3'x2" SMC (Rainier)	2010	2010
h picket	A	3b	1	3'x2" SMSR	210	210
h picket	A	3a	1	3'x2" SMSR	190	190
h ski	D	10d	1	180 cm x ~2.5", 2' deep	2492	2492
h ski	D	12d	1	180 cm x ~2.5", 2' deep	4126	4126
picket	B	18	1	2'x2" SMC (Joe's)	192	192
picket	B	17	1	2'x2" SMC (Joe's)	269	269
picket	B	15	1	2'x2" SMC (Joe's)	139	139
picket	B	14	1	2'x2" SMC (Joe's)	213	213
picket	B	3	1	2'x2" SMC (Joe's)	180	180

picket	B	2	1	2'x2" SMC (Joe's)	125	125
picket	B	10	3	2'x2" SMC (Joe's)	542	181
picket	D	4.1 d	1	2'x2" SMC (Rainier)	1300	1300
picket	D	6d	2	2'x2" SMC (Rainier)	2985	1493
picket	B	19	1	3'x2" SMC (Joe's)	309	309
picket	B	6	1	3'x2" SMC (Joe's)	471	471
picket	D	4.1 d	1	3'x2" SMC (Rainier)	1450	1450
picket	B	5	2	3'x2" SMSR	725	363
picket	B	4	3	3'x2" SMSR	623	208
picket	A	2a	1	3'x2" SMSR	180	180
picket	A	2b	1	3'x2" SMSR	220	220
picket	A	5b	2	3'x2" SMSR	520	260
picket	A	5a1	2	3'x2" SMSR	180	90
picket	A	5a2	2	3'x2" SMSR	210	105
bollard	A	8a	1	10'dia x 2' deep, padded	1180	1180
bollard	A	9a	1	10'dia x 2' deep, not padded	1000	1000
bollard	C	3	1	9'w x 11'L, padded	1050	1050
bollard	D	17d	1	7'w x 10'L not padded	4083	4083
deadman	A	11b	1	1x1x2' pack burried ~2' deep	950	950
self-arrest	D	14d	1	human	405	405
self-arrest	D	20d	1	human	277	277
self-arrest	D	21d	1	human, butt up	441	441
self-arrest	D	24d	1	human, butt up	656	656
self-arrest	D	25d	1	human, butt up	707	707
self-arrest	D	26d	1	human, butt up	520	520

Tools: 25 in2 fluke = 6.5 x 3.875" w/ 45 deg angle
31 in2 fluke = 6.25/7.5 x 4.5 w/ 50 deg angle
41 in2 fluke = 7/8 x 5.5" w/ 35 deg angle
42 in2 fluke = 7.75 x 5.375" w/ 25 deg angle
83 in2 fluke = 10.75 x 7.75" w/ 45 deg angle
"h picket" means horizontally placed
"picket" means vertically placed, tipped back ~15 degrees
SMC pickets = T-stock, 2" wide, several lengths
3' x 2" SMSR picket = V-rail, 2"wide x 72 in2 long
self arrest: presence of pack made no difference

5
8
54
62
4
7
20
5
3
3
3
4
1
1

ıt Mt. Rainier