Ice Climbing Anchor Strength: An In-Depth Analysis

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***Abstract**:*

Ice climbing anchors are seemingly simple, yet have a mystique that surrounds their use and overall strengths. Not all ice climbing anchors are used in a standard configuration.

Placing an ice screw into an already existing ice screw hole is called re-boring. Re-boring of ice screws is a common practice among ice climbers. Re-boring is typically preferred when placing a screw to avoid creating adjacent holes that could serve as a potential fracture propagation point.

We evaluated re-boring strengths for several ice screw designs to determine the strength as a function of length of screw. Slow pull tests were performed, and the results were compared with prior data from drop testing on ice screws. Static pull testing using lake ice was compared with drop testing on waterfall ice and found to be a good substitute test medium.

In addition, we evaluated Abalakov anchors (a.k.a. V-thread anchors), with 7mm Perlon cord as well as 1" tubular webbing in different configurations. Their strengths were then compared with that of the single re-bored ice screws.

The nature of ice is a continually changing medium and hard to predict in the field. However, the actual strengths shown from our testing methods in the real-world environment make a strong case for the strength of re-boring. Recently, re-bored holes in a freezing environment were found to be strong enough in most configurations. Abalakov ice anchors were also found to be strong, provided that enough ice area was enclosed by the anchor. Placing Abalokov anchors vertically appeared to be stronger than placing them horizontally. Precautions and recommendations for use of ice climbing anchors stem from our evaluation of the data.

I. INTRODUCTION:

Ice climbing anchors have traditionally been shunned as not being strong anchors, especially when compared to rock. Perhaps, this arises in part from the fact that ice is a poorly understood medium and has a mystique about it due to its perceived unpredictable nature at times.

In technical ice climbing, the technique of re-boring (Figure 1) has been utilized over the years. Several legitimate scenarios exist for re-boring an ice screw. Finding a good placement for an ice screw is often difficult. With the advent of more traffic on ice climbs, the usual "easy" ice screw placements may have already been used. What remains is the conundrum of choosing where to place a screw. One option is to place a screw into an already existing hole that was created by a previous ice climbing party. That hole is an uncontrolled factor as to what type of screw was used initially, when it was drilled, and what environmental conditions have occurred since the hole was left behind.

Figure 1 Placing a screw into an existing hole is called re-boring.

Another scenario that often occurs is when an ice climber may be leading a pitch of ice at their difficulty threshold, find an old hole that appears to be usable, and wonder if it is reasonable to use that hole. A dull screw that doesn't "bite" into the ice to start a new hole is always problematic. Time can be of the essence when the climber looses all strength and risks a dangerous fall. Re-boring an ice screw seems to be a quick alternative to creating an entirely new hole and can save the climber strength by decreasing the amount of times placing the ice screw.

Other legitimate scenarios exist for re-boring an ice screw. The above are merely examples and are non-exhaustive.

Much conjecture has been created, leading to dogma, about how good these placements are or are not. We now know that "psychological protection" (a piece of protection that the climber may think dubious) produces less of an impact force on the system, even if a piece fails, rather than just climbing quickly for the belay stance. "Running it out" produces larger forces than a fall that pulls out a piece of protection because of the residual fall factor after a failed anchor point[1]. We also know that air pockets (not aerated ice) near ice screw placements are bad and cause fracturing of the ice more readily. Ice is a difficult medium to understand, and its fracture mechanics can be explained to a certain degree[2], but inherently, it is not possible to anticipate the nature of fracture, propagation, and collapse in the field as yet.

Other types of ice anchors exist, such as the bollard and Abalakov. The bollard is fairly passé and somewhat dangerous on ice, because of decapitation and slipping, but it is used in the alpine environment. The threaded Abalakov, however, is used extensively.

Threaded Ice Anchors: Abalakovs (a.k.a. V-threads)

Vitaly Mikhaylovich Abalakov, a Russian, is credited for the innovation of drilling into the ice in two places, such that the two drilled holes would come together as far back as possible to create a continuous hole. A rope or piece of cord could then be threaded through and used as an anchor, as shown in Figure 2. This technique is also commonly known as a "V-thread." With it, a climber can retreat without leaving much, if any, gear behind, thereby, be able to abseil many pitches in a row. Commonly, climbers will leave a piece of webbing or cordage behind in the anchor so that climbing ropes do not become stuck in the back of the Abalakov. At other times, the V-thread is used as an anchoring point for climbing competitions, rescue anchors, top rope anchors, or other applications.

Figure 2 shows a traditional horizontally made Abalakov ice anchor.

Anchor strength studies were first evaluated and published in Canada by Joe Josephson[3]. Since then, many people have accepted that the Abalakov anchor as a standard rappel anchor for descent from ice climbs. The pendulum then swung in public opinion that the Abalakov was stronger than an ice screw. This led to the idea that an Abalakov anchor was strong enough to belay from in the multi-pitch climbing environment.

II. HYPOTHESES:

The working hypotheses to be tested are:

1) Re-bored ice screws are strong enough* to arrest a UIAA[4] fall.
2) The over driven ice screw in a shorter original hole is strong enough* to take a leader fall on.
3) Shorter screws placed in longer screw holes are as strong as longer screws placed in longer screw holes.
4) Abalakovs are stronger than ice screws.
5) Abalakov strength is directly related to the area it encompasses rather than the orientation.

* Strong enough to hold 7-8kN [1]

III. BACKGROUND:

Fortunately, there are very few case reports for failed re-bored ice screws resulting in injury. The lack of published literature available limits our ability to perform a retrospective study.

Climbers gain experience through feedback mechanisms, both positive and negative. Therefore, the thought process is that "if an anchor doesn't fail, then that type of anchor should be good enough to use the next time." In other words, those who never fail a placement will gain a sense of comfort from experience. Fortune smiles on climbers most of the time, but it is impossible to know how strong is "strong enough" without formal testing where failure is observed.

Much has been assumed about re-boring. The comments typically heard include: "the placements aren't strong enough to hold a fall; it's a waste of time to place them; and they're psychological pro."

When considering whether an ice screw is stronger than an Abalakov /V-thread placement, unpublished preliminary testing proposed that Abalakov anchors are weaker than single screw placements in streambed ice[5].

The actual mechanics of ice fracture has been studied, especially in the marine ice realm. Although it is not our focus to evaluate these characteristics, it is important to understand that freshwater ice fails in uniaxial tension via transgranular cleavage[6]. The mechanics of tensile failure are described in both nucleation and propagation[2] . A direct correlation exists between grain size and fracture propagation: the larger the grain size, the greater the propagation of fracture. Brittle compressive failure is more complex and fails via longitudinal splitting in unconfined fresh-water ice [7].

Research by Schulson indicates that ice strength depends on the square root of grain size, rate of loading, and temperature.

For ease of testing, a static pull test was used to load ice screws placed in lake ice. The grain size of ice typically found on ice walls and lake ice will be about the same, so grain size effect for lake ice and wall ice will be similar. Likewise, the temperature of the lake ice and waterfall ice were comparable and not considered to be a source of strength difference between lake ice and waterfall ice.

The ratio of rate of loading between slow pulls and drop test are on the order of 1000x. At really slow rates of loading (i.e., moving as slow as a glacier), ice will be ductile, with the yield strength increasing with load rate. For faster loading rates, the strength of ice decreases with rate of loading. Based on laboratory testing by Schulson, failure stress at 1e-3/sec (slow pull) are about 20% higher than strain rates at 1e-1/sec (drop test). Thus, for our slow pull test, we could expect some increase in the strength of ice under slow pull compared to drop testing. Differences may also exist due to the difference between lake ice and waterfall ice. Lake ice will likely have fewer defects than waterfall ice.

IV. METHODS:

We did slow pull tests on ice screw re-boring configurations based on ice screws placed at a positive angle relative to perpendicular of the ice face. This positive angle is considered the proper configuration for lead climbing[8,9].

Slow pull test in accordance with the Cordage Institute standard rate of pull of 0.5”-1.0” per second powered by a hydraulic ram was used for pull testing of the screws. The ram was anchored to the ice. Ice and air temperatures (Figure 3), as well as times and details of each test, were recorded for the slow pull tests at Echo Lake , Colorado (Figure 4), located near the town of Pagosa Springs. Several slow pull tests were done on Abalakovs in Ouray at the new Kid’s wall, since the ice was convenient and homogenous.

Figure 3 (left) measuring air and ice temperatures (°C); (middle) measuring depth and angle of holes (cm); (right) simple evaluation of fracture characteristics.

Figure 4: (left) showing the nature of homogenous lake ice as a control medium; (middle) slow pull tests on waterfall ice in Ouray; (right) the drop testing grounds for waterfall ice in Ouray Ice Park.

For our testing, we needed to use the same medium for making a direct comparison analysis. We chose lake ice for pull testing, not only because it is a good control but also for ease of access and reproducibility of our testing worldwide.

A control medium with variability as small as possible is hard to find. The UIAA has recently published a safety standard[10] on how ice screws are to be tested in order to receive a Comité Européen de Normalisation (CEN) rating for sales in countries. YTONG[11] has also been considered for ice screw testing, but this medium is not readily available for our testing purposes.

Our drop testing was performed at the Ouray Ice Park, Colorado. Two routes were used to perform the drop testing on, both located at the Lower Bridge: *Rhythm Method* WI5 (the same route that we used in 2005-06), and the *2008 Competition Route* (on the ice section between the mixed rock climbing and the diving board) that had not been used by any ice climbers prior to our testing. This site provided a good control area. The two routes are on distinctly different aspects in the Uncompahgre Gorge in order to get a better sampling of the ice at the Ouray Ice Park.

Ice Screws

The general specifications of the UIAA are outlined in Figure 5. There is no mention of any testing that has been performed, where ice screws had been tested in re-bored holes. Our approach did not follow UIAA specifications. The UIAA specifications call for strength testing for screws loaded in shear and loaded in tension. The UIAA specifications were designed to test the strength of the screw, not the strength of the screw placement in ice. The specifications require that the screw not fail below a critical load. Our testing considered loads in shear only and included the tests where each screw was loaded to ice failure.

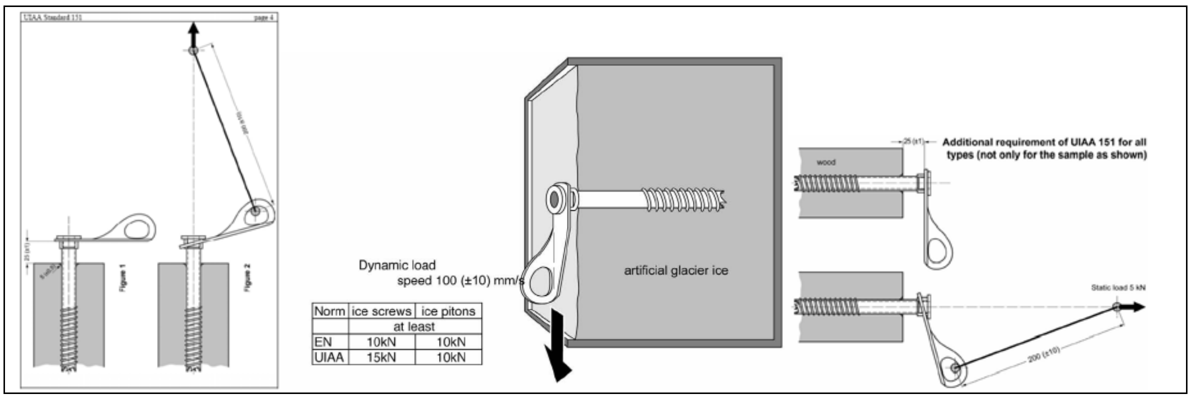

Figure 5: UIAA specifications for testing ice screws in different mediums. (permission of use by the UIAA)

We performed two drop tests on re-bored and over drilling in combination using a longer screw in a shorter hole. The results were as strong as if it were a new hole. We then focused our remaining tests on the worst-case scenario, whereby a climber would come upon a long hole and only have a short screw for placement. We alternated holes drilled by the same and different manufactures in conjunction with using a short screw

We repeated testing on some screws that had either been used in drop testing already or used in a slow pull test. The rationale is that we were not as concerned with the strength of the screw as we were with the strength of the re-bored hole. Interestingly enough, the strengths of the screws did vary somewhat as a function of multiple uses, as some screws would break before the re-bored hole failed. If the screw showed obvious signs of fatigue, then it was not used again. In one case during a slow pull, the screw fractured at the midpoint of the tube; several other times the eye of the screw would fracture. Screw failure was not observed for new screws that had not been used in prior testing.

Orientation:
There is still debate, as well as inconclusive results, from screw angle placement[11,12,13]. It has been fairly well documented that on static pull testing, "confirming that the most effective threads are those near the hanger (and that the reverse thread orientation may be stronger than regular thread orientation)…the holding strength does not depend significantly on thread type, but rather on the radial and axial dimensions of the screw". The general strength of an ice screw is based on loading rate duration rather a faster loading rate[13].

It is well understood that placement of an ice screw, whether in dynamic shock loading or slow pull testing, produces the strongest results when NOT placed in a negative angle (i.e., using the screw in a levering configuration). So, from somewhere between 0° and +20° is the ideal angle, and that was our target range for testing re-bored screws.

RESULTS:

Re-bored Ice Screw Results:

A statistical comparison of drop test results and slow pull testing is presented in Table 1. These results indicate drop tests on waterfall ice and slow pull tests on lake ice produced similar results.

Drop testing statistics	
Mean	10.6
Standard Error	1.3
Standard Deviation	4.9
Minimum	3.9
Maximum	22.0
Count	15.0
Confidence Level(95.0%)	2.7

Slow pulls in Lake Ice - ALL Screws	
Mean	11.1
Standard Error	0.6
Standard Deviation	3.7
Minimum	5.5
Maximum	19.7
Count	38.0
Confidence Level(95.0%)	1.2

Table 1 Re-bored ice screws; all results by testing type.

Redline Failures - Re-bored Ice Screws	kN
Beverly/Attaway 2005-06 - Drop Tests (non-re-bored)	10.14
Beverly/Attaway 2007-08 - Drop Tests	10.58
Beverly/Attaway 2007-08 - Slow pulls Lake Ice	11.09

Table 2 The overall averages of failure forces

A vary high failure strength (22.5 kN) for a re-bored ice screw was achieved by leaving a re-bored screw overnight with a test mass of 80kg hanging from it for more than ten hours. The temperatures recorded were less than -30°C in the Ice Park that night. There was no evidence of melt-out from the ice screw, even with a test mass hanging from it. This correlates well to Schulson's evaluation that ice becomes stronger (<25% when cooled from -5°C to -20°C).

Angle

The regression line shown in Figure 6 shows that 14° ± 5° is the optimal angle for re-bored ice screws. Placing a screw at 0° or as great as 25° shows a marked decrease in overall strength.

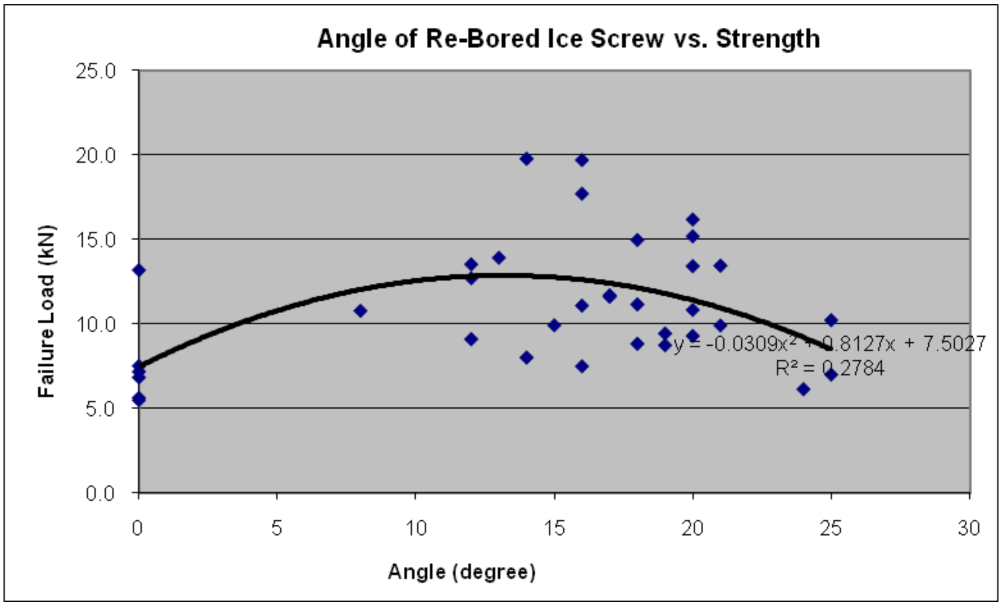

Figure 6 A regression line indicates the area where the strongest + angle is.

Length of Re-Bored Ice Screw

For slow pull testing on lake ice, ice screw strength was a strong function of length. In slow pull tests, as shown with the blue line in Figure 7, even having a few extra centimeters can, on average, increase the strength of the ice screw placement.

The dependence of strength on screw length was not as evident for drop testing. There still remains a slight positive correlation, and one might attribute that to chance alone. Only a limited number of drop tests were performed on long screws. Drawing a conclusion on strength-versus-length for ice screws loaded with drop test will require more data.

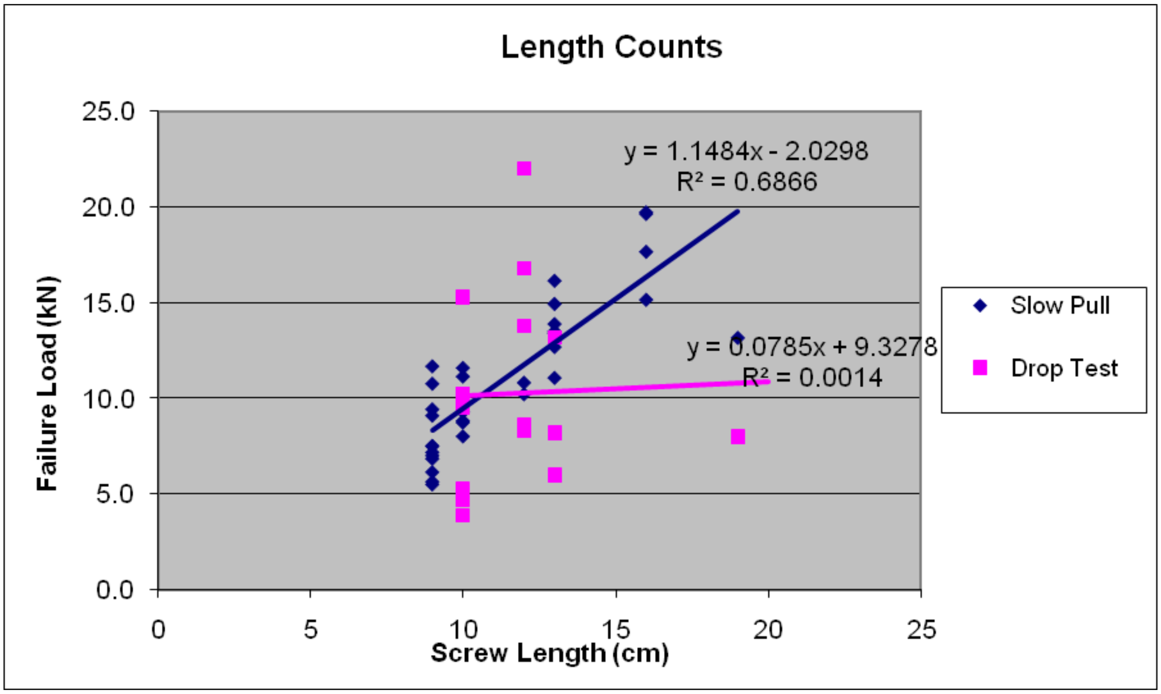

Figure 7 Length of Re-Bored screws placed into long holes. A regression analysis shows the strength correlation for slow pulls and drop tests.

Results: All Threaded Ice Anchors

In regards to our Abalakov Ice anchors, we found the following data to be quite insightful and very interesting.

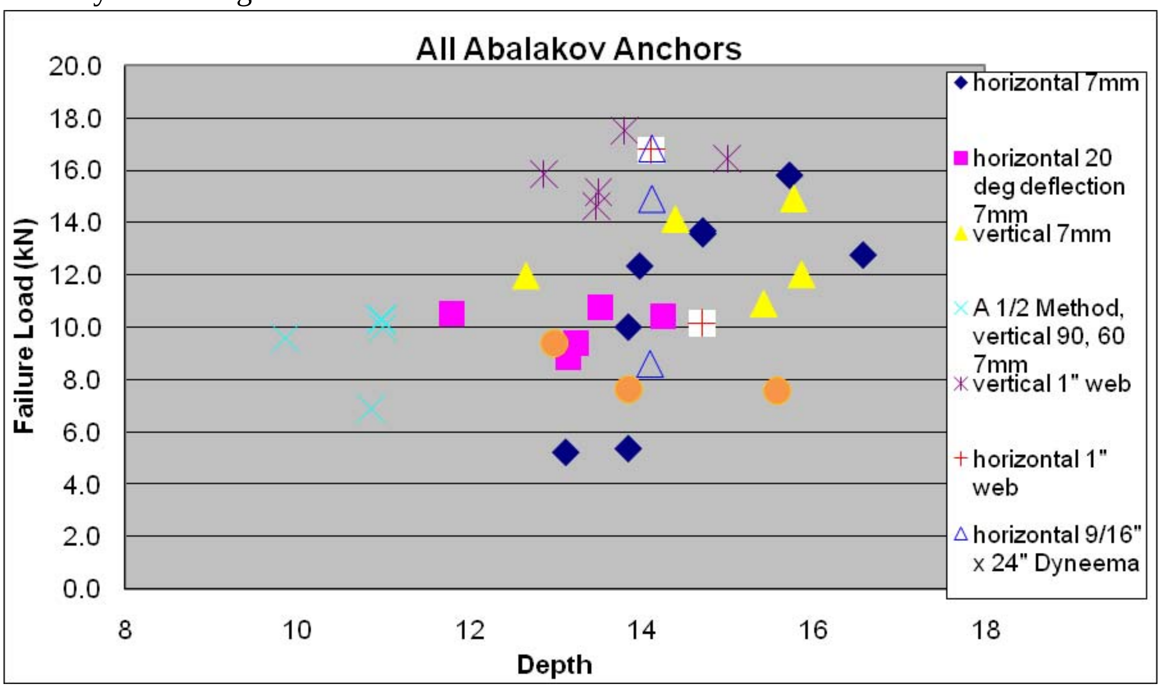

Figure 8 A scatter plot of threaded ice anchors by type.

We tested several different configurations of Abalakov anchors. Temporal variations were limited by pre-setting all the anchors and pulling each anchor to failure within a couple of minutes of each other. Figure 8 shows the data for all Abalakovs, while Figure 9 depicts the protocol and techniques used in the slow pull process.

Figure 9 (left) shows multiple Abalakov slow pull testing in action; (middle) logging data and quickly moving the pull testing device from anchor to anchor; (right) showing the strongest Abalakov configuration and material used (1" tubular webbing).

Test results showed that Abalakov anchor strength was a strong function of geometry and orientation.

Ice fails by fracture in zones of tension more easily than in compression[2,6]. In our testing, the failure mechanisms for Abalakovs and ice screws resulted in a large segments of ice above the anchor point failing in tension. The ice located below the Abalakov and located below the screw are both placed in compression and actually have a higher failure load due to the increased strength of ice under compression.

Large amounts of ice were displaced superiorly from the zone of tension when visually compared to the inferior zone (towards the force applied), as shown in Figure 10. Notice that both ice anchors have similar modes, with lots of ice seen coming out above the anchor and almost no ice noticed coming out below the anchor.

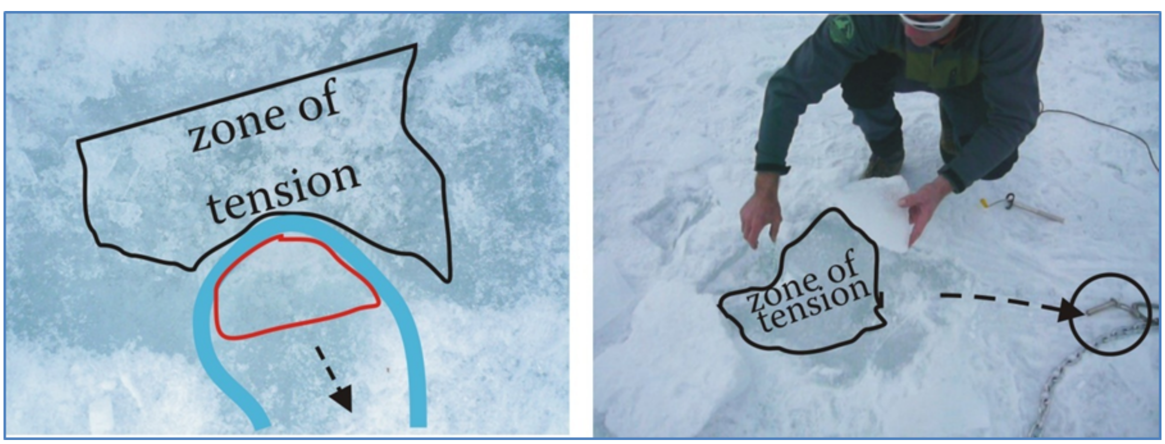

Figure 10 Left: Abalakov anchor. The dotted lines represent the direction of the force vector applied: (left) the blue line shows where the 7mm Perlon Abalakov cordage was. The red line indicates where the bulb was released. **Right: Ice screw anchor**. Notice the large amount of ice superior/above to ice screw from the zone of tension.

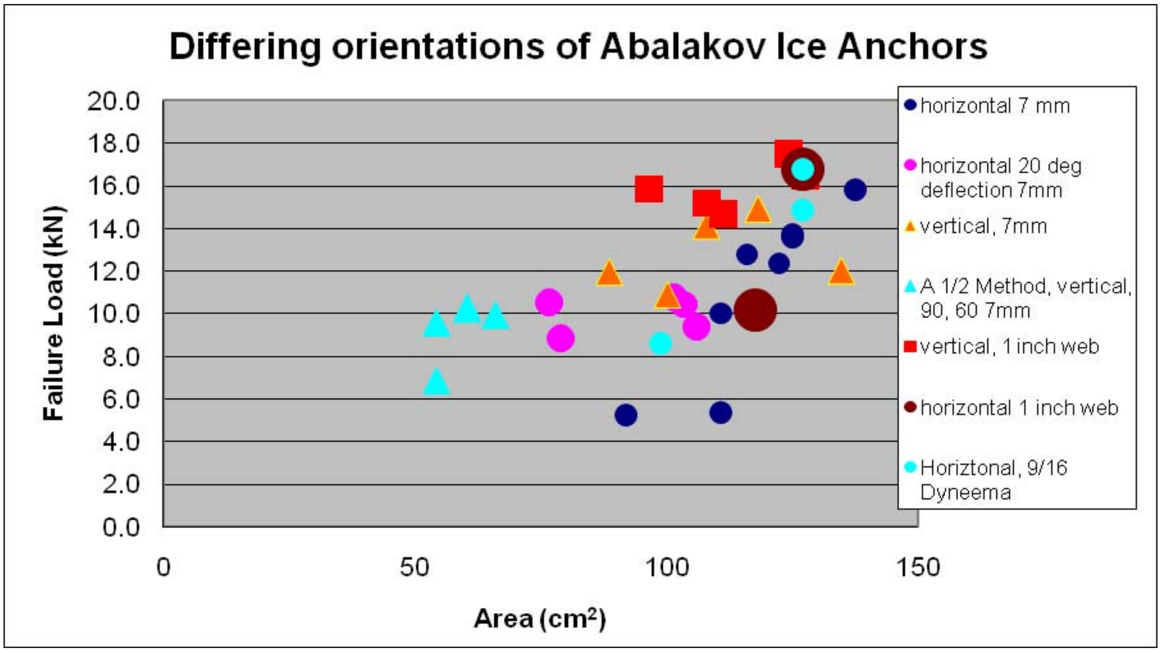

Figure 11 Differing orientations of Abalakovs vs. total strength with good grouping.

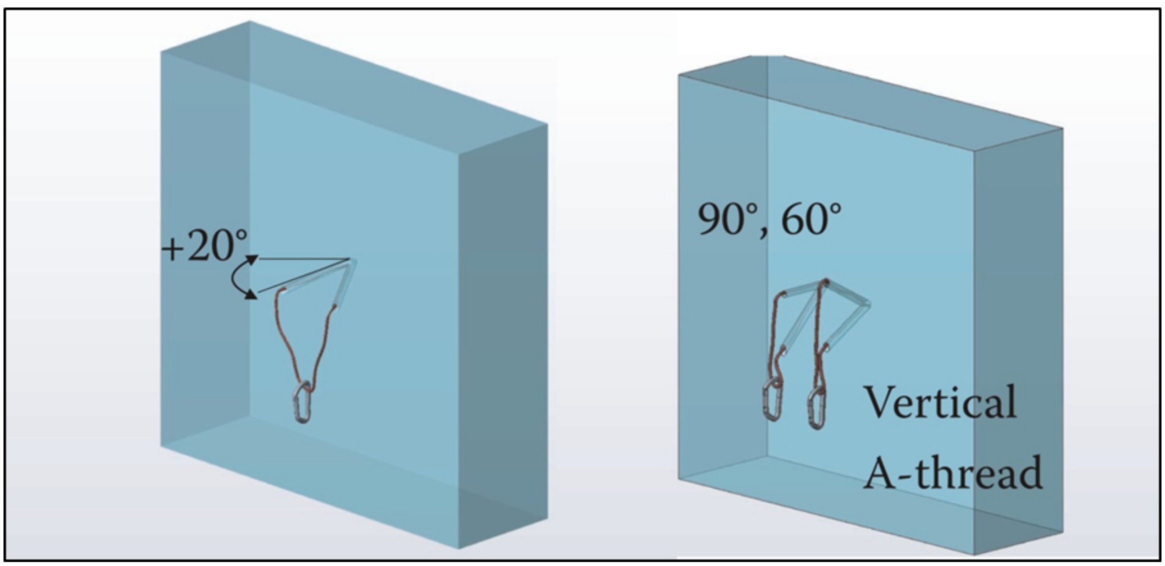

Figure 12 Digital pictograph of the other orientations tested. (left) a V-thread with both holes places at +20 degrees and adjoining in the back; (right) A-threads (Anderson threads) with the tope hole 90 degrees perpendicular and the other using the 60x60x60 degree method.

Figure 11 shows a plot of Abalakov anchor strength as a function of the area enveloped by the anchor. Test results indicate that the more total area enveloped by the Abalakov, the higher the ice anchor’s strength.

Enclosed area is not the only mechanism upon which the strength is based. The strength is also a strong function of the anchor orientation. A vertical (A-thread) placement increases the overall anchor strength.

Figure 13 (left and middle) strongest orientation; (middle) strongest orientation and material-vertical 1" tubular webbing single loop; (right) weakest of the three, but still strong enough*.

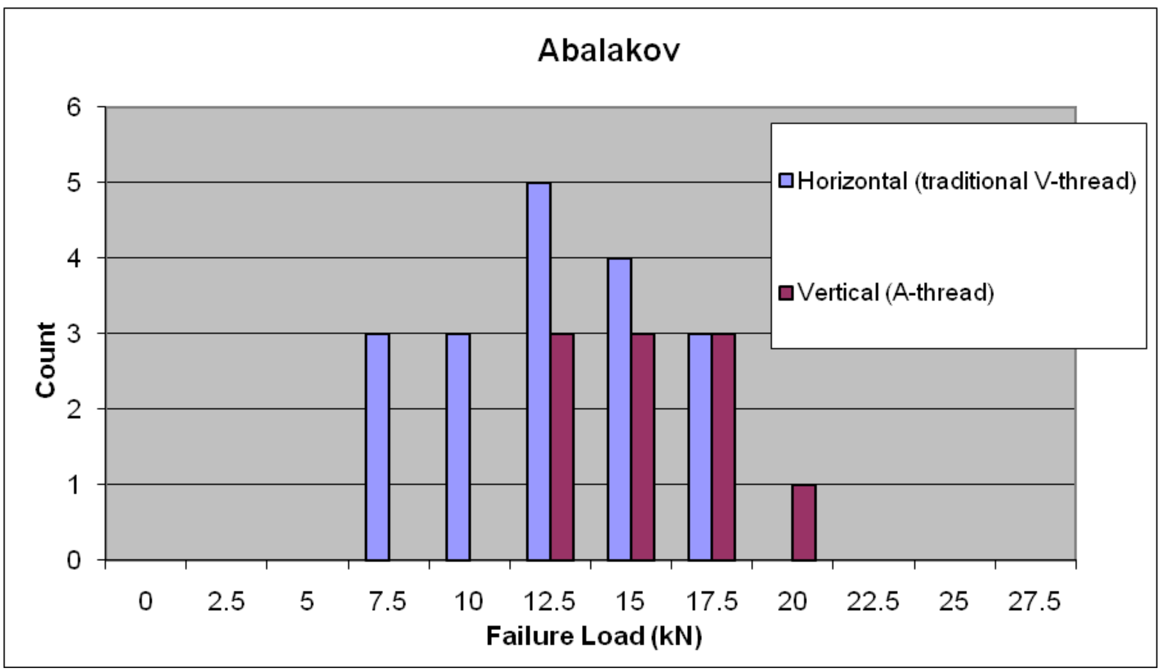

Figure 14 Orientation of Abalakov vs. Strength, both sets of anchors with 1" tubular webbing.

Figure 13 displays the configuration and type of materials used to make the threaded ice anchors. Figure 14 shows how the strongest orientation was in the vertical configuration. This is also outlined in Table 3.

From our testing data, 1" tubular webbing tied off with a standard water knot/ring bend was measured to be the strongest on a consistent basis.

data for horizontal (V-threads)			data for vertical (A-threads)	
	kN			kN
Mean	11.3		Mean	14.4
Standard Error	0.8		Standard Error	0.7
Median	10.3		Median	14.8
Standard Deviation	3.6		Standard Deviation	2.1
Sample Variance	12.7		Sample Variance	4.6
Range	11.6		Range	6.6
Minimum	5.2		Minimum	10.9
Maximum	16.8		Maximum	17.5
Count	18.0		Count	10.0
Largest(1)	16.8		Largest(1)	17.5
Smallest(1)	5.2		Smallest(1)	10.9
Confidence Level(95.0%)	1.8		Confidence Level(95.0%)	1.5

Table 3 Data comparison of traditionally placed horizontal (V-threads) vs. vertically placed (A-threads).

The good news is that all of the configurations and materials used were strong enough* to hold abseilers/rappellers with a significant safety margin from a single anchor point. Testing showed that anchors could fail at below expected climber fall (7.5 kN) forces and should be backed up if in any doubt.

Comparison of Types of Ice Anchors:

Figure 15 compares the strength of ice screws drilled into virgin ice, with the strength of re-bored ice screws testing in both drop test and slow pull. All three were shown to have comparable normal distribution curves with most failures occurring within the 10-15kN range. Also plotted on this graph is the strength of the Abalakov anchors in both the horizontal and vertical orientation.

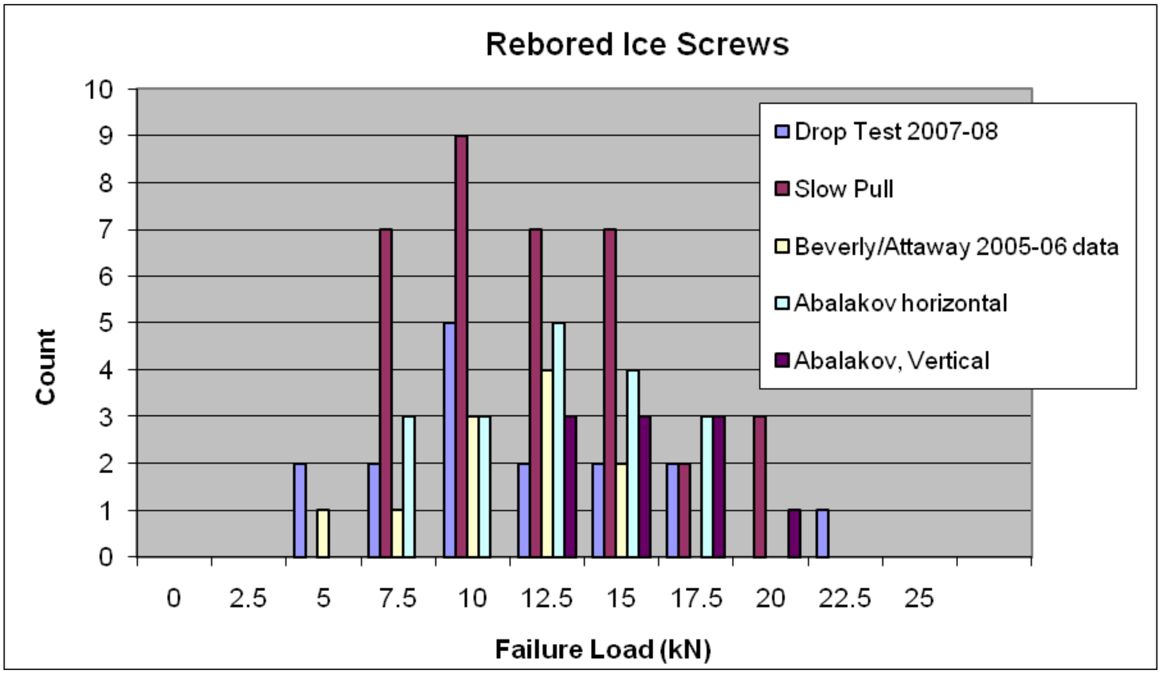

Figure 15 Re-Bored Ice Screws compared to overall strengths of our drop and slow pull tests to our previous data from 2005-06 as well as to our data from Abalakovs in both horizontal and vertical orientation.

Figure 16 compares the strength of re-bored ice screws with the horizontal and vertical Abalakovs anchors. While the number of tests may be too limited to draw conclusions, the preliminary testing results show that longer ice screws are stronger than Abalakovs. Vertical Abalakovs are stronger than Horizontal Abalakovs. Horizontal Abalakovs are on average about the same as re-bored short screws. The data also shows that a considerable spread exists in all anchor strengths, with the potential for failure in loads below the expected (7.5 kN) loads generated by ice climbers.

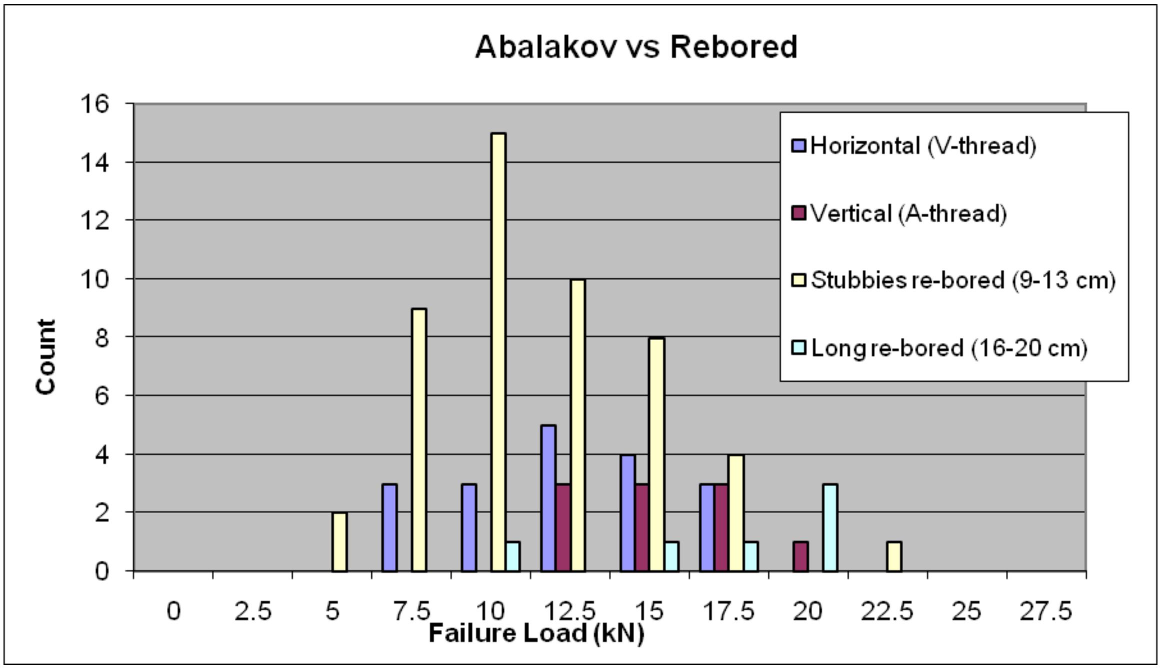

Figure 16 Shows peak force compared to ice anchor type and configuration.

Discussion:

Using a re-bored ice screw as a first placement off a multi-pitch climb is a sufficient load reduction method that can aid the falling climber from placing the entire impact force on the anchor system that results from a residual fall factor.

The most risk of high impact forces on an anchor/anchor system in climbing is when a climber is starting from a hanging belay. A single ice anchor (screw or Abalakov) is unlikely to arrest a high impact force from a lead climber in this position. In Figure 17, the leader would have been better off not to have clipped the anchor and thereby taking a fall factor of 2, as the rope would place a lesser peak force to the system than in the configuration shown.

Figure 17 Multi-pitch scenario: Leader falling onto a single ice anchor (in this case a single horizontal Abalakov) that the belayer is also attached to in the UIAA fall test scenario, a potentially deadly combination.

Our sample size is still what we consider to be small and non-exhaustive. The spread is large, and ice is a variable medium. Learning good skills at where and when to place ice screws remains an art, although our science is helping us to compose a better picture of ice anchor behavior experienced in real-world conditions.

CONCLUSIONS:

These tests were performed in what the authors consider to be "good ice[1]." Lake ice appears to be a good testing medium for comparison analysis to waterfall ice that is homogenous.

1) Based on the variability of anchor strength observed in our test results, we must accept the null hypothesis that re-bored ice screws are too weak to withhold a UIAA fall factor ***all*** of the time. They are, however, stronger than expected and compare closely with an ice screw placed in virgin ice.
2) Re-bored ice screws are nearly as strong as freshly drilled holes. It is likely that any refreezing process that decreases the diameter of the hole over time is of benefit for a re-bored screw.
3) A re-bored ice screw that is left in frozen temperatures overnight will likely freeze in quite solid, even with a mass of 80 kg suspended from it, and not experience "melt-out," even if placed in a positive angle.

4) The greater the area an Abalakov anchor has, the more likely it is to be a stronger anchor. So, save the longest screw for the belay to make an Abalakov using 60° x 60° x 60° as the best guide line for angle drilling.
5) We accept the null hypothesis that a single ice screw, even a short re-bored screw, is generally about the same in strength as a horizontal Abalakov anchor.
6) The longer the ice screw is, the stronger the ice anchor will be, regardless of whether it is a freshly placed screw or a re-bored screw.
7) There is no significant difference when comparing the three manufacturer’s brand ice screws when placed into an old hole of the same or different manufacturer.
8) Reverse threads did not appear to make a difference in any regard.
9) The optimum angle placement is >8° and <16° from our regression analysis.
10) The vertical Abalakov is superior in strength to the tradition horizontal or other configurations tested. We call this the “A-thread”, since discussions with Vince Anderson inspired investigation into other configurations.
11) Drop Test data on waterfall ice were weaker than Slow Pull test data on lake ice. Rescue anchors for slow pulls will likely act as stronger placements than when climbers fall onto ice screws.
12) NEVER use a single anchor (A-thread, V-thread, or ice screw) as the only anchor when high forces are expected, as seen with multi-pitch climbing.

FUTURE RESEARCH:

1) Numerical simulations to evaluate zones of tension and compression for a better understanding into the mechanics of ice anchor fracture for both Abalakov-style ice anchors and ice screws.
2) Evaluate other types of screws that have diameters and threads of different sizes.
3) It is likely that a re-bored screw may be stronger when compared to the alternative of placing a new hole next to an old hole. Nearby holes can result in stress concentrations and act as a fracture nucleation site. We did not evaluate the possible reduction in anchor strength due to nearby drill holes.
4) A slight strength difference was observed between 7 mm cord and 1” tubular webbing. More testing may be needed to see if this strength difference is significant.

Note: Overdriving (red-lining) ice screws in the drop testing environment is dangerous. Flying ice debris, ice screw missiles, snapping ropes, and the general objective hazard of being in the vertical ice environment, plus having to record data and also be aware of everything else going on, is taxing as well as expensive. Many thanks goes out to Angie Lucht for her help in drop testing and to Nic McKinley for his efficient help on the slow pull tests performed on lake ice.

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[1] Beverly, M, Attaway, S. Measurement of Dynamic Rope System Stiffness in a Sequential Failure for Lead Climbing Falls. ITRS, 2006.
[2] Schulson EM, Brittle Failure of Ice. Eng Fracture Mechanics 68 (2001) 1839-87.
[3] Joe Josephson. "Ice Anchor Review", The Canadian Alpine Journal, 76, 1993, pp66-67.
[4] http://www.theuiaa.org/upload_area/cert_files/UIAA101_DynamicRopes.pdf
[5] http://video.google.fr/videoplay?docid=1863958284744514965
[6] Schulson EM, Baker I. Robertson CD, Bolon RB, Hanimon RJ, Fractography of Ice. J. Mater Sci Lett 1989;8:1193-4.
[7] Smith TR, Schulson EM, the Brittle Compressive Failure of Fresh-Water Columnar Ice Under Biaxial Loading. Acta metall mater 1993;41(1):153-63.
8 Beverly, M.; Attaway, S. Dynamic Shock Load Evaluation of Ice Screws:
A Real-World Look. ITRS, 2005.
[9] Harmston, Chris. Climbing no 172 (Nov 97), pp106-115
[10] http://www.theuiaa.org/upload_area/cert_files/UIAA151_IceAnchors01-2004.pdf
[11] Cracco, S., Meneghetti, G. Holding Strength of Ice Screws in YTONG Concrete. Session of the UIAA Safety Commission. Sept. 2006.
[12] Heshka. Holding Strength of Climbing Ice Screws vs. Placement Angle. Annual Report Scholarly Activity Committee. 2005.
[13] Blair, K., Custer, D., Alziati, S., Bennett, W. The effect of load rate, placement angle, and ice type on ice screw failure. 5th International Engineering of Sport Conference, 2004.